

ANALYSIS AND SIMULATION OF
HIGH FREQUENCY LINK CONVERTERS AS A POWER FLOW CONTROLLER
IN FLEXIBLE AC POWER TRANSMISSION SYSTEMS

By

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To my loving wife, Bo-Young

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LIST OF SYMBOLS

L_u : Transmission line inductance plus filter inductance

L_f : Filter inductance

L_1 : Transmission line inductance

X : Transmission line impedance

L_t : Tank circuit inductance

C_t : Tank circuit capacitance

f_h : Frequency of the tank circuit

f_1 : Frequency of the ac system

ω_1 : The angular velocity of the ac system

ω_h : The angular velocity of the tank circuit of HFLC

V_t : Tank voltage

V_{tp} : The peak value of tank voltage

I_{st} : The external current flowing into the tank circuit

I_{stp} : The peak value of the external current, I_{st} .

V_{ll} : Line-to-line voltage at HFLC output terminal

V_l : Line voltage at HFLC output terminal

V_m : Magnitude of the line voltage

I_l : Line current

I_m : Magnitude of the line current

S : The instantaneous power flow

P_1 : Real power flow from system 1

P_2 : Real power flow to system 2

P_1 : Real power flow from ac system to tank circuit

P_m : Real power flow from ac power system to tank circuit through input converter

Q_1 : Reactive power flow from system 1

Q_2 : Reactive power flow to system 2

Q_1 : Reactive power flow from ac system to tank circuit

Q_m : Reactive power flow from ac power system to tank circuit through input converter

W_o : Energy stored in tank circuit for the previous half cycle of tank voltage

W_t : Energy stored in tank circuit for the present half cycle of tank voltage

ϕ : Phase angle of line voltage

δ : Phase angle difference between the line voltages

θ : The phase angle between voltage and current.

ΔV : The 60 Hz component of the output voltage synthesized at the terminal of HFLC

ΔW : The ripple of the tank energy

ΔI_m : The small change of the line current in linearization

$\Delta \theta$: The small change of the phase angle of line current in linearization

ΔV_t : The ripple of the tank voltage

ΔP : The small change of the real power flow in linearization

ΔQ : The small change of the reactive power flow in linearization

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This dissertation investigates the feasibility of the high frequency link converter (HFLC) as a power flow controller in a flexible ac power transmission system (FACTS). The HFLC has a single-ungrounded, parallel-resonant tank circuit, switching devices, and a current reference waveform pulse density modulation (CRWPDM) controller employing zero-voltage switching to reduce switching loss.

It is shown that the HFLC can serve as a HFLC cycloconverter, a HFLC series compensator, a HFLC phase shifter or a HFLC shunt compensator in order to control the power flow accurately and quickly in the ac power transmission system. The control system of each HFLC application was developed. In order to evaluate the performance of HFLC's as power flow controllers in ac power transmission systems, complete computer simulation models of the HFLC's using Electro-Magnetic Transients Program (EMTP) were developed. The computer simulation models include the HFLC circuit, the control system, the measurement system and the ac power transmission system to form integrated test models. A simple two-bus one-branch ac power transmission system, and

a 13-bus reduced model of the Florida Power and Light (FP&L) 500 KV transmission system were used as ac power system models.

The following characteristics were evaluated by the EMTP simulation study: steady-state performance, transient performance, harmonics and filtering requirements, the control of HFLC's in the simple ac power system and the damping effect and the protection of HFLC's in FP&L system. Comparisons between HFLC's were also made. Potential problem areas were identified for successful implementation of HFLC's as the power flow controller in FACTS.

CHAPTER 1 INTRODUCTION

One potential candidate as a flexible ac power transmission system (FACTS) element is a high frequency link converter (HFLC). This study investigate the feasibility of the 5 KHz HFLC in order to improve the performance of the 500 KV ac power transmission system. The HFLC circuit can serve as a HFLC cycloconverter, a HFLC series compensator, a HFLC phase shifter or a HFLC shunt compensator in an ac power transmission system. The study includes the analysis, the design, and the computer simulation of HFLC and demonstrates FACTS concepts using HFLC in a practical ac power transmission system. The control system of each HFLC is developed to control the power flow in an ac power system. The Electro-Magnetic Transient Program (EMTP) is used as a tool of the computer simulation study of HFLC.

1.1 Background

Power flows in a conventional ac power transmission system cannot easily be directed along specific, desired paths by changing the magnitude of the node voltage or by shifting the phase of the node voltage. As a result, ac power transmission system suffers from parallel-path or loop flows [4]. Most of the devices now available for improving ac power transmission system performance, such as a phase-shifting or tap-changing transformer, are mechanically switched. However, in mechanically switched

systems, the speed of the power system response to control signals is slow and the maintenance costs are high. Because the present ac power transmission systems were not designed to cope with the future magnitude of bulk power transfers, the ac power transmission system must be expanded. However, new transmission lines take a long time to build and are very expensive. Furthermore, ac power transmission systems also have some problems in the area of long-distance bulk-power transmission because of right-of-way consideration, line losses, reactive power consumption, and stability problems [20]. Thus, the ac power transmission system can be regarded as insufficiently flexible [18].

High voltage direct current (HVDC) transmission systems have been considered as an alternative to ac power transmission since the thyristor was developed. The use of the HVDC transmission system has grown significantly due to its many functional, economical and environmental advantages [20]. The typical advantages are as follows:

- * Fast solid state control of power flow
- * Improved stability
- * Long distance bulk power transmission
- * Less space required for right-of-way
- * Asynchronous tie

Compared to the ac power transmission system, an HVDC system is very accurate and fast in the power flow control. However, HVDC transmission systems have several problems [10, 20, 37]:

- * Reactive power consumption
- * Coupled control of real and reactive power

- * Possibility of commutation failure
- * Filtering requirements for low order harmonic components
- * High cost

Present advances in semiconductor technology have produced much faster gate turn on and off devices which can be self-commutated. Among new self-commutation switching devices, the Static Induction Thyristor (SITH) and the fast GTO are the most promising switching devices for high power application. SITH have been demonstrated to have 4 KV, 400 A and 2-3 μsec switching time capability [28]. The switching capability and the switching loss of the SITH have been reported to be less than 1% of the processed power. GTO thyristors have shown potential in a 10 MVA, 10 KHZ system and have the potential for use in a 100 MVA, 100 KHz system with resonant switching [39]. Another promising switching device is the MOS-controlled thyristor (MCT) which can theoretically work at 2500 V, 500 A [38].

Advanced semiconductor technology allows faster switching times for thyristors and GTOs. As a result, the switching frequency of converters using these types of switching devices has been increased up to several tens of kilohertz [6]. High frequency switching converters are becoming popular because high frequency switching converters provide several benefits which are essential in power conversion systems [9, 15]:

- * Reduced size of reactive elements
- * Small high frequency transformers
- * Low distortion output
- * Fast control

* Adaptability to different types of loads/sources

The methods of energy control determine the classes of control mode and converter topologies. Examples of control modes are simple phase control, pulse amplitude modulation (PAM), pulse width modulation (PWM), and pulse density modulation (PDM). Phase control has been used mainly for the low switching frequency application due to switching loss [34]. For many years, PWM has been preferred because of its simple operation, low harmonics and voltage control capability. However, in order to obtain low harmonics, the switching frequencies of a PWM converter must be relatively high. Since the PWM switching events simultaneously cause high current and voltage in the switches, the switching loss of the PWM converter can become restrictive [7].

A recent popular alternative to PWM is the resonant mode of operation [32]. Resonant converters use the variable switching frequency to achieve PAM. Resonant mode switching operation or "soft switching" has also been found attractive in high power, high frequency switching applications because it reduces switching losses by switching at zero voltage or zero current [22, 23, 27]. This also facilitates commutation. For high frequency and high power applications, the simplicity of PWM and the low switching loss of the resonant mode are usually combined in order to achieve better performance [17, 36].

PDM control has been introduced to address the switching loss issue [34]. PDM control can be applied to dc/dc, dc/ac, and ac/ac converters. In PDM control, switching frequency should be high enough to achieve low distortion output.

High frequency switching operation converters have appeared in various forms in recent study of power electronics. One of them is a high frequency link converter [15, 34]. HFLC has a parallel resonant tank and a switching circuit which synthesize the desired output voltage and interfaces naturally with an inductive transmission line. A 20 KHz HFLC for space power application was developed to connect a DC source to a variable frequency polyphase output [34]. The HFLC concept was first proposed by P.M. Espelage and B.K. Bose [9], who applied a single-phase 2-4 KHz voltage link to interface DC or AC loads/sources. L. Gyugyi and F. Cilibulka used 36 thyristors for a naturally commutated high frequency converter in which a three-phase high frequency transformer and a three-phase tank circuit were introduced [15]. The above studies using the phase angle controlled cycloconverter have shown high switching losses. Therefore, HFLCs using phase angle control have been considered too inefficient, too expensive and too impractical for high power applications where efficiency is of prime importance. However, recent improvements in high power semiconductor switches, especially in the thyristor family of devices (GTO, SITH, MCT), have changed this outlook [28, 38].

Zero voltage (or current) commutation methods using resonant circuits have been introduced to reduce the switching losses. A unipolar link structure using zero voltage switching of the GTO device was introduced [7]. The area comparison pulse density modulation method using the zero voltage switching has been introduced to synthesize the low frequency waveform from the high frequency pulses [34]. The parallel-output series-resonant converter provided the high frequency sinusoidal ac voltage to the PDM converter. The PDM converter using naturally commutated thyristors suffers from

switching loss and distorted output when it works under low power factor [34].

Improvements in very high power semiconductor devices such as light triggered SCR's and GTO's, and improvements in power conversion techniques have opened the possibility of improving the problems in HVDC systems and even in ac transmission system [4, 14]. Therefore, the high technology can make the present transmission system more flexible. A flexible ac transmission system (FACTS) could eliminate loop power flows and provide a more sophisticated degree of control through a combination of high-power electronic devices and computerized system automation [4].

There are three basic methods to increase the power transfer capability of an ac transmission line: maintaining the proper voltage profile of a transmission line, reducing the impedance of the transmission line, or increasing the power angle between the node voltages [14]. These have been achieved by using synchronous condensers, shunt capacitor banks, series capacitors and phase-shifting, tap-changing transformers [13, 25, 29]. Each device improves the performance of the power system by controlling the reactive power of the system.

Synchronous condensers play a major role in voltage and reactive power control by maintaining voltages under various operating conditions and improving stability of the ac power system [25]. They have been also applied to HVDC transmission systems to supply the portion of reactive power demanding of a HVDC converter. For economic reasons, the switched shunt capacitors banks have been preferred to synchronous condensers for subtransmission power levels [25]. The shunt capacitors increase the power transfer, improve transient stability and improve the voltage profile in transmission

lines. The shunt capacitors are typically installed close to the load for minimum line losses and for maximum voltage control [14].

Series capacitors reduce the total effective reactance of an ac transmission line by inserting capacitance in series with the ac transmission line. The series capacitors can be located remote from the load and they improve steady-state stability and transient stability, reduce transmission line loss and allow better power flow on parallel circuits. However, series capacitors can cause subsynchronous resonance problem [25].

Phase-shifting, tap-changing transformers control both the magnitude of the bus voltage and the phase angle, and they can be used to minimize real power loss of the ac power system [40]. They also increase the stability margin, but should be located near the generator to reduce its reactive power consumption [25].

Except the synchronous condenser, the above devices are controlled by mechanically discrete adjustments. These mechanical characteristics respond slowly to the control signal and hinder performance due to their slow reaction time. In addition, the maintenance costs are high.

Since the development of high power thyristor valves (SCR's), they have played a major role in modern high power electronics. They have made possible the use of HVDC system to provide better performance to ac power transmission systems. Each of three basic methods to increase the power transfer capability of an transmission line can be achieved by using high speed thyristor-based devices. The implementation of reactive power control using thyristor-based devices has been achieved by thyristor-controlled reactors and thyristor-switched capacitors for regulating line voltage [13, 35],

controllable series compensators are possible for controlling line impedance, and thyristor-controlled phase shifting transformers are possible for controlling the phase angle [1, 25]. The thyristor-based devices respond sufficiently fast with continuous adjustments. However, the aforementioned advanced semiconductor devices like GTOs make possible new implementations of static var compensators, controllable series compensators, and phase shifters [14, 16, 30].

1.2 Objectives

The objective of this research is to explore the feasibility and potential benefits of HFLCs as a power flow controller in ac power transmission systems. To accomplish this goal, detailed 5 KHz HFLC models for EMTP computer simulation studies are developed. The HFLC model includes a ungrounded-single tank circuit, a switching devices, a current reference waveform pulse density modulation (CRWPDM) controller, a tank voltage controller, a power flow controller and a 60 Hz ac power transmission system. The performance of the developed HFLCs as a power flow controller are evaluated by EMTP simulation study. The parameters to evaluate the performance of HFLCs include steady-state operation, harmonics in output, transient operation, tank voltage ripple, power flow control capability and damping effect.

1.3 Overview

This section presents a brief overview of the remainder of this dissertation. There are four important parts to this dissertation. The first part analyzes the operation of the

HFLCs and the second part explains the HFLC topologies based on the application purpose, the third part describes the control method of HFLCs to synthesize the output, while the fourth part shows the simulation results of HFLCs in an ac power transmission system.

This chapter has reviewed the problems of the ac power transmission system, the advanced technology in switching device and power conversion, the FACTS concept, and the old and new approaches to solve the ac power transmission system problem. The objectives of the study are also addressed in this chapter.

Chapter 2 discusses the structure of a typical HFLC which has a parallel-connected tank circuit. The zero voltage switching technique to reduce switching losses, the use of the pulse density modulation to synthesize the required output waveform, the magnitude of the tank voltage for proper operation of HFLC in the ac power system are all explained. The relation between the capacitor size of the tank circuit and the ripple of the tank voltage is explained. The inductive filtering requirement is also explained. Switching device candidates and commutation methods are briefly described.

Chapter 3 describes topologies of a HFLC cycloconverter, a HFLC series compensator, a HFLC phase shifter and HFLC shunt compensator. The characteristics of each HFLC circuit in an ac power transmission system are discussed and compared to each other and its conventional circuit. The detailed structures of HFLCs are also presented.

Chapter 4 describes how the current reference waveform PDM (CRWPDM) controller synthesizes the required current. The voltage reference waveform PDM

(VRWPDM), the harmonic elimination PDM (HEPDM) method, and the hysteresis PDM (HPDM) method are also discussed as an output control method. It is also discussed how the power flow controller generates the current reference corresponding to the required power, and how the tank voltage controller keeps the tank voltage within proper range. The power flow controller and the tank voltage controller are combined to build a high-level control system for the HFLC.

Chapter 5 presents the simulation results based on the developed HFLC models. The HFLC circuit developed in Chapter 3 and the controller developed in Chapter 4 are combined. The simulation results demonstrate the performance of HFLCs in the terms of harmonics, filtering requirements, steady state and transient operations. It is also shown that HFLCs damp out the oscillatory power flow in an ac power system. EMTP is used as a tool for the simulation study.

Chapter 6 summarizes the important conclusions of this dissertation and suggests directions in which this work can be extended. In Appendix A, the measurement algorithm of the HFLC control system is explained. In Appendix B, the concept of the circulating power flow is explained. In Appendix C, the various transfer functions for the tank voltage controller are explained. In Appendix D, the load flow results of Florida Power and Light (FP&L) System are presented. In Appendix E, EMTP simulation data for the FP&L system is shown. In Appendix F, harmonic analysis results of the voltages and currents in an ac power system with a HFLC cycloconverter are presented. In Appendix G, the design methods of the tank capacitance of HFLC cycloconverter and HFLC series compensator are explained.

CHAPTER 2 HIGH FREQUENCY LINK CONVERTER

This chapter explains the structure of a typical high frequency link converter (HFLC), the zero voltage switching method, the voltage reference waveform pulse density modulation (VRWPDM) method, the design of a high frequency (HF) tank circuit as a HF voltage generator, inductive filtering, switching devices and commutation method.

2.1 Structure of High Frequency Link Converter

Fig. 2.1 shows the detailed structure of a typical HFLC in which the tank circuit is parallel-connected to the three-phase ac power system. As shown, the HFLC has an ungrounded tank circuit, an optional HF transformer, switching devices, snubbers to protect switching devices from high di/dt and dv/dt, inductance filters to suppress harmonic components in the output current, and a PDM controller.

The tank circuit of the HFLC in Fig. 2.1 has a capacitor, C_t , and an inductor, L_t , which determine the high resonant frequency, f_h . The resonant high frequency f_h is approximately expressed as:

$$f_h \approx \frac{1}{2\pi\sqrt{L_t C_t}} \quad [Hz] \quad (2.1)$$

The tank voltage generated by the tank circuit crosses the zero voltage at every half cycle

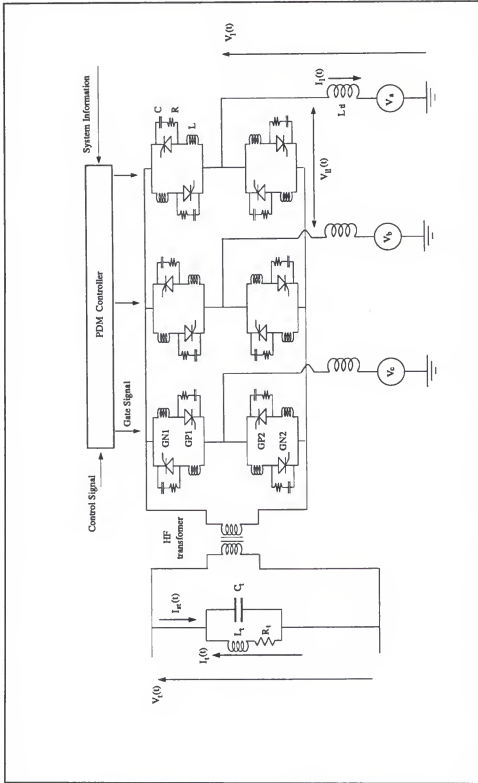


Fig. 2.1 High frequency link converter connected to three-phase ac power system.

of the resonant frequency, f_h . Fig. 2.2 shows the ideal 5 KHz tank voltage and the zero crossing instant of the tank voltage, $V_i(t)$. In the practical HFLC, the peak value, V_i of the tank voltage is not constant because the capacitor size of the tank circuit and the operating condition of the ac power system have an effect on the ripple of the tank voltage. The ripple of V_i has effects on the harmonics in the converter output. To reduce harmonics in the output is important for the ac power system to operate properly.

The HF transformer in Fig. 2.1 is optional. It can be used to step up or down the HF tank voltage. Therefore, 60 Hz transformers in the ac power system can be replaced by the high-frequency transformer together with the HFLC. However, it is likely that the majority of utility applications of the HFLC as flexible ac transmission system (FACTS) elements would be used as an upgrade to existing facilities, where 60 Hz transformers are already in place. Therefore, even if the HF transformer proved to be cost-effective, their application would probably be limited to network expansion projects [5].

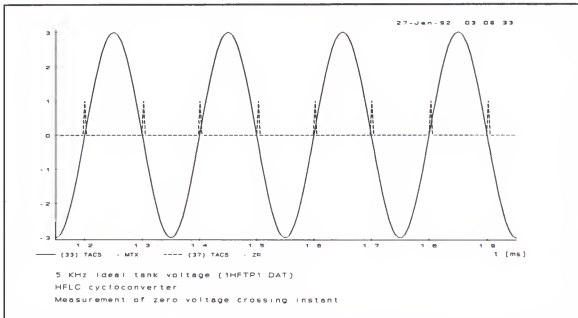


Fig. 2.2 Measurement of zero voltage crossing instant of 5 KHz tank voltage, $V_i(t)$.

The HF transformer has several power losses like core loss, copper loss and insulation loss. The efficiency of the HF transformer depends on the technology of HF magnetic materials.

The technology of the HFLC depends mainly on the technology of semiconductor switching devices which determine the switching loss and conduction loss. The HFLC uses the zero voltage switching to reduce the switching loss. Fig. 2.3 shows the switching voltage and the switching current of the HFLC using the zero voltage switching. Four switching devices in each phase are necessary to realize four-quadrant operation of the HFLC. Each switching device has forward and backward blocking capability. The snubber circuit consists of resistor, R, capacitor, C, and inductor, L. The snubber circuit is required for the protection of switching devices. In this study, it is

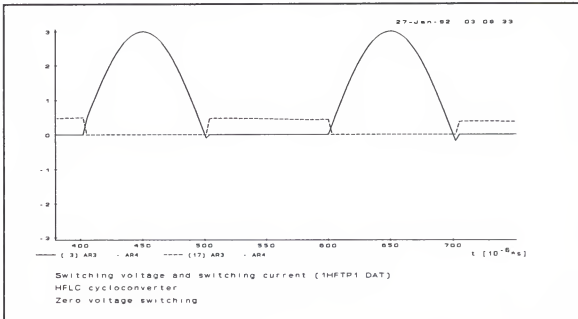


Fig. 2.3 The zero voltage switching of high frequency link converter.
Plot shows the switching voltage and switching current.

assumed that the switching devices can be ideally turned off and on at the zero crossing time.

The inductance, L_d in Fig. 2.1 includes an inductance of ac transmission line , the leakage inductance of a 60 Hz transformer of the ac power system and the filter inductance required to suppress harmonics in the output current [26].

The PDM controller in Fig. 2.1 generates gate signals for the switching devices to produce the required output. The PDM controller requires detecting of zero voltage instants, power flows, line currents and line voltages as feedback signals. The switching occurs at the time which tank voltage crosses zero, and the zero voltage switching reduces switching losses. The controller uses the reference waveform pulse density modulation (RWPDM) to synthesize the required output voltages or currents.

2.2 Zero Voltage Switching and Pulse Density Modulation

A phase-angle control scheme was used in the HF cycloconverters in the early stages [15]. The phase-angle-controlled cycloconverter is frequently used when one-step power conversion from an ac voltage source is required, but it is not suitable for systems where the switching frequency is an order of magnitude higher because of the high loss associated with each switching [34]. So the zero voltage switching and the area comparison pulse density modulation (ACPDM) control was introduced. ACPDM is another name for VRWPDM.

Fig. 2.4 shows the concept of zero voltage switching and how an ACPDM controller generates the required low frequency output voltage from high frequency tank

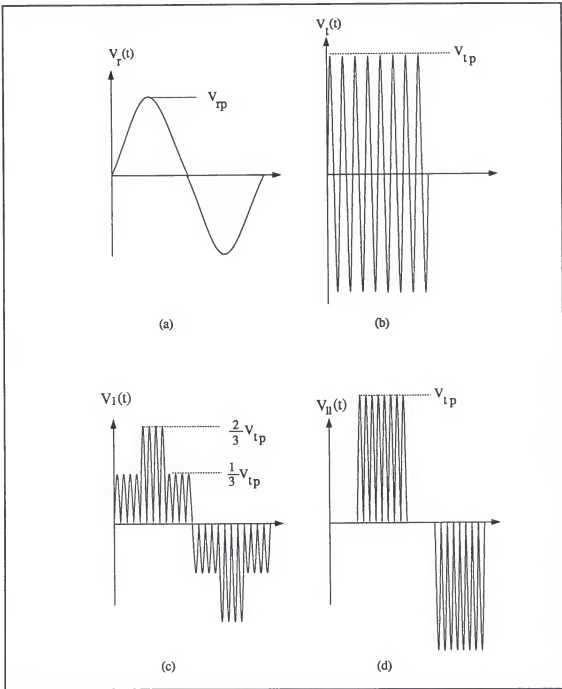


Fig. 2.4 Pulse density modulation for the minimum tank voltage operation; the 60 Hz component (a), the high frequency tank voltage (b), the synthesized line voltage (c), the synthesized line-to-line voltage (d).

voltage. The low-frequency required voltage is shown in Fig. 2.4 (a) and the HF tank voltage is shown in Fig. 2.4 (b). The required line voltage $V_r(t)$ is written as

$$V_r(t) = V_{rp} \sin(\omega_f t) \quad (2.2)$$

where V_{rp} is the peak value and ω_f is the angular fundamental frequency. The tank voltage $V_t(t)$ is expressed as

$$V_t(t) = V_{tp} \sin(\omega_h t) \quad (2.3)$$

where V_{tp} is the peak value of HF tank voltage and ω_h is the angular high frequency. The tank voltage, $V_t(t)$, crosses through zero twice per cycle of the high resonant frequency, f_h , of the tank circuit. The switching points are at discrete multiples of the tank voltage zeros, which minimizes the switching losses and the switching related device voltage stresses.

Fig. 2.5 shows the block diagram of VRWPDM controller. In this scheme, the area under the reference voltage, V_r , is compared with the area of the synthesized voltage, V_t . The error signal in Fig. 2.5 is written as

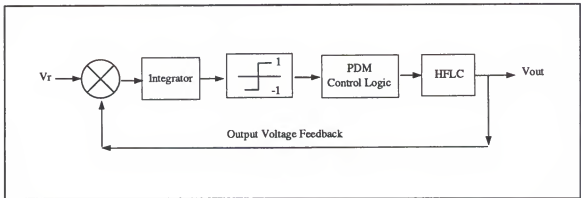


Fig. 2.5 Voltage feedback scheme for PDM controller of HFLC.

$$\epsilon(t) = \int (V_r(t) - V_i(t))dt \quad (2.4)$$

It is quantized into one of two possible levels depending on its polarity. The PDM control logic tries to change the polarities of error by monitoring the tank voltage and determining the switching pattern at each voltage zero. The HFLC output voltage is synthesized from the positive and negative pulses of the half cycles emitting from the high frequency tank voltage. Synthesized line-to-neutral voltage $V_{ln}(t)$ and line-to-line voltage $V_{ll}(t)$ are shown in Fig. 2.4 (c) and (d).

The VRWPDM controller minimizes the error $\epsilon(t)$ between the desired reference wave $V_r(t)$ and the output wave $V_i(t)$ synthesized from the half cycles of tank voltage $V_{ln}(t)$. Even though the synthesized output $V_i(t)$ differs from the sinusoidal waveform, it can be resolved into a fundamental sine wave and its harmonics by Fourier Analysis. Therefore $V_{ln}(t)$ can be expressed as

$$V_{ln}(t) = V_{dc} + \sum V_{Ln} \sin(n\omega t + \theta_n) \quad (2.5)$$

where ω is the fundamental angular frequency, V_{dc} is the dc component, and V_{Ln} is the n^{th} harmonic magnitude. The harmonic component, V_{Ln} , of $V_{ln}(t)$ for the minimum tank voltage operation are approximately expressed as [26, 31]

$$V_{Ln} = \frac{8V_p}{3\pi^2 n} (1 + \cos(\frac{n\pi}{3})) \quad (2.6)$$

where n is the number of harmonics (n is odd number). From equation (2.6), the magnitude of the fundamental component, V_{L1} , is written as

$$V_{L1} = 0.405 V_p \quad (2.7)$$

This is the maximum magnitude of the fundamental component of the synthesized output voltage. $V_1(t)$ in Fig. 2.4 (c) can be approximated by the fundamental component, V_{L1} , as the following:

$$V_L(t) \approx 0.405 V_p \sin(\omega_L t) \quad (2.8)$$

The error $\epsilon(t)$ in equation (2.4) is minimized when the fundamental component of $V_1(t)$ is close to $V_L(t)$. Equation (2.8) shows that the magnitude of synthesized output voltage depends on the magnitude of tank voltage and the general relationship between the peak tank voltage and the peak value of line voltage is expressed as [34]

$$V_L \approx 0.405 m V_p \quad (2.9)$$

where,

$$0 < m \leq 1 \quad (2.10)$$

where m is a modulation factor which gives the limits of control capability [34]. When m equals 1, HFLC is in the saturation mode. Harmonics in the output voltage of the PDM controller depends on the modulation factor.

The relationship between the modulation factor, m , and the tank frequency, f_b , can be expressed by the voltage-time area error [34]. The voltage-time area error is maximum when the synthesized HF pulse of $V_1(t)$ in Fig. 2.4 has the polarity opposite of the reference voltage at the peak of the 60 Hz reference voltage. The ratio of the maximum voltage-time area error to the area under one half-cycle of the reference

voltage, V_r , is defined as %Error, which is expressed as [34]

$$\%Error = \frac{(\frac{4}{3} + 0.405\pi m)f_t}{2(0.405)mf_h} \times 100 \quad (2.11)$$

Equation (2.11) is a guideline for choosing the high frequency f_h . Fig. 2.6 shows the %Error versus the high frequency. It shows that %Error of the synthesized output voltage at the 5 KHz resonant frequency is less than 5%, for m greater than 0.635.

Another method to choose the resonant frequency of the tank voltage is the harmonic elimination method [5, 31]. The resonant frequency should be high enough to produce sufficient precision in switching angle to remove the low component of harmonics in $V_1(t)$.

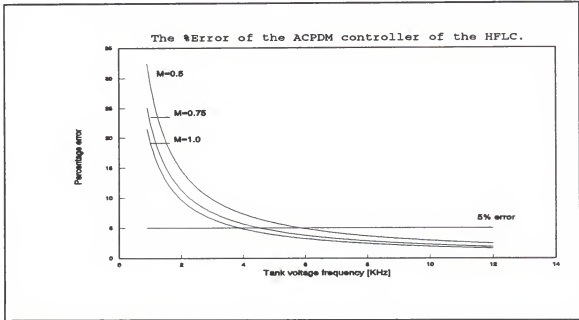


Fig. 2.6 The ratio of the maximum voltage-time area error to the area under one half-cycle of the 60 Hz reference voltage. The HFLC circuit has a single-ungrounded tank circuit.

2.3 Tank Circuit Design

The HFLC requires a HF ac voltage generator. In a previous study [34], a parallel-output series-resonant converter was used as a HF voltage generator. For an ac power transmission application, the HFLC handles only reactive power and harmonic power. Therefore, the high frequency voltage generator can be replaced by an oscillating inductance-capacitance tank circuit shown in Fig. 2.1. In the tank circuit, the oscillation of energy between inductor and capacitor occurs at the natural resonant frequency, f_b , of the tank circuit. The tank energy, W_t , and the peak value of the HF tank voltage, V_t , can be expressed as

$$W_t = \frac{1}{2} C_t V_\varphi^2 \quad (2.12)$$

The relationship between the circulating tank current, I_t in Fig. 2.1 and the tank voltage is written as

$$\frac{1}{2} C_t V_\varphi^2 = \frac{1}{2} L_t I_\varphi^2 \quad (2.13)$$

where I_φ is the peak value of circulating current in the tank circuit. In a practical tank circuit, I_t generates the ohmic loss

$$I_t^2 R_t \quad (2.14)$$

and the external current, $I_m(t)$, from the ac power system supplies/absorbs real power

$$V_t(t) I_m(t) \quad (2.15)$$

to/from the capacitor in the tank circuit. Therefore the energy in the tank circuit is

exchanged in every half cycle of tank voltage, with the ohmic losses in the tank circuit, between the tank circuit and the ac power system. Therefore the peak value of tank voltage, V_{tp} , has ripples. Fig. 2.7 shows that $V_t(t)$ of the HFLC, which has a $0.7 \mu\text{F}$ capacitor and a 1.8 MV peak tank voltage, has ripples in the peak values, and Fig. 2.8 shows the energy flowing from the ac power system to the tank circuit of the HFLC during every half cycle of $V_t(t)$. By the linearization of equation (2.12), the relationship between the ripple of tank voltage and the changing of energy in the tank circuit can be expressed as

$$\Delta V_t = \frac{\Delta W_t}{C_t V_{tp}} \quad (2.16)$$

Equation (2.16) shows that the ripple of tank voltage can be reduced by a large capacitor or by a high tank voltage. A high tank voltage causes stress on the switching devices of the HFLC. The peak value of tank voltage is given in equation (2.7). Equation (2.13) shows that a bigger capacitor requires greater circulating tank current to generate the same magnitude of tank voltage at a given frequency, f_h . Therefore, the capacitor size should be minimized to a size which produces an acceptable ripple in the tank voltage, because a large ripple may cause distortion in the synthesized output.

The ripple in the tank voltage can be indirectly expressed by the energy ripple in the tank circuit as

$$\Delta W_m = \frac{W_t - W_o}{W_o} \quad (2.17)$$

where W_o is the stored energy in the tank in the previous half cycle of HF tank voltage,

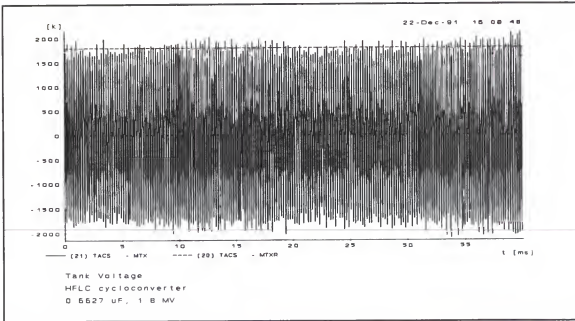


Fig. 2.7 The instantaneous tank voltage, $V_t(t)$, of HFLC cycloconverter with 1.8 MV reference in steady-state operation. The peak values of the line voltage is 408.25 KV and the peak value of the line current is 2828 A. The phase angle, θ , is 30° . The capacitance of the 5 KHz tank circuit is $0.6627 \mu\text{F}$.

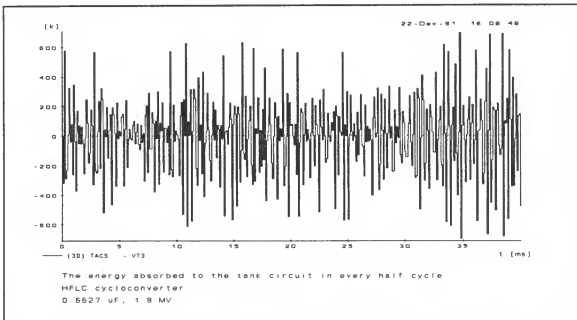


Fig. 2.8 The energy absorbed to the tank circuit of HFLC cycloconverter for the half cycle of the 5 KHz 1.8 MV tank circuit.

and ΔW_m is the normalized ripple. From Fig. 2.1, the tank voltage is written as

$$C_t \frac{dV_t}{dt} = I_{st} + I_t \quad (2.18)$$

In equation (2.18), it is assumed that $I_{st}(t)$ is constant for the half cycle of the tank frequency. By solving equation (2.18) for $V_t(t)$ with equations (2.1) and (2.13), the tank voltage can be approximately written as

$$V_t(t) \approx \left(-\frac{I_{stp}}{\omega_h C_t} + V_{sp} \right) \sin(\omega_h t) \quad (2.19)$$

where I_{stp} is the peak value of $I_{st}(t)$ flowing into the tank circuit from the ac power system. Fig. 2.9 shows $I_{st}(t)$. I_{stp} depends on the line current. By substituting equation(2.19) in equation (2.12), equation (2.17) can be written as

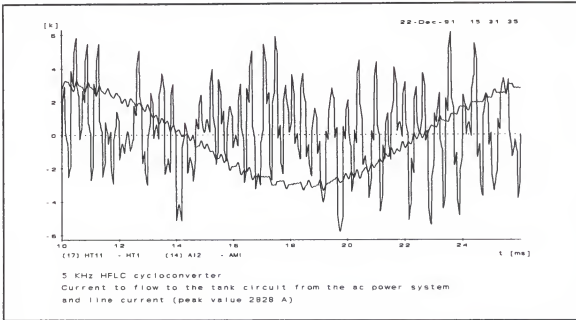


Fig. 2.9 The current, $I_{st}(t)$, flowing to the 5 KHz tank circuit of the HFLC cycloconverter and the line current, $I_t(t)$, in 408 KV, 2828 A ac power system.

$$\Delta W_m = \frac{(V_\varphi + \frac{I_{sp}}{\omega_h C_t})^2 - V_\varphi^2}{V_\varphi^2} \quad (2.20)$$

which can be transformed to

$$(\Delta W_m)V_\varphi^2 - 2\frac{I_{sp}}{\omega_h C_t}V_\varphi - (\frac{I_{sp}}{\omega_h C_t})^2 \approx 0 \quad (2.21)$$

By solving the equation (2.21) for C_t , the capacitor is written as

$$C_t = \frac{I_{sp}}{\omega_h V_t (\sqrt{1 + \Delta W_m} - 1)} \quad (2.22)$$

where I_{stp} is the biggest value of $I_m(t)$ for the worst ripple. Equation (2.17) can be expressed by the tank voltage ripple, ΔV_t , as

$$\Delta W_m = \frac{(V_t + \Delta V_t)^2 - V_t^2}{V_t^2} \quad (2.23)$$

It is transformed to

$$\Delta W_m = 2(\frac{\Delta V_t}{V_t}) + (\frac{\Delta V_t}{V_t})^2 \quad (2.24)$$

By the normalization of the tank voltage ripple, equation (2.24) is transformed to

$$\Delta V_m^2 + 2\Delta V_m - \Delta W_m = 0 \quad (2.25)$$

By solving equation (2.25) for ΔV_m , the relationship between the normalized tank voltage ripple, ΔV_m , and ΔW_m is written as

$$\Delta V_m = \sqrt{1.0 + \Delta W_m} - 1.0 \quad (2.26)$$

Now the capacitor size can be designed for the tank voltage ripples by using equations (2.22) and (2.26). Then the inductance L_t of the tank circuit is determined by the tank frequency as the following:

$$L_t \approx \frac{1}{\omega_h^2 C_t} \quad (2.27)$$

Fig. 2.10 shows the capacitor size versus the peak tank voltage with 10% ripples of energy. The capacitor of tank circuit, C_t , in equation (2.22) is good for the proper operation of the HFLC in the ac power system. Fig. 2.7 showed the changes of the peak tank voltage for a 0.7 uF capacitance. Fig. 2.11 shows the changes of the peak tank

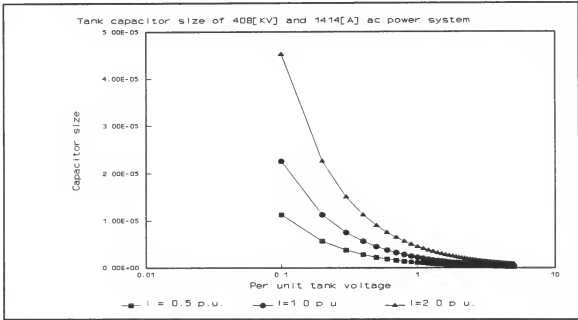


Fig. 2.10. The required capacitor size of 5 KHz HFLC tank circuit. The per unit base is 408 [KV] for the line voltage, 1414 [A] for line current and 60 [Hz] for the frequency. The plots were drawn for the 10% ripple in energy of the tank circuit.

voltage for a 2 μF capacitance. Fig. 2.11 shows smaller ripples in the tank voltage than Fig. 2.7.

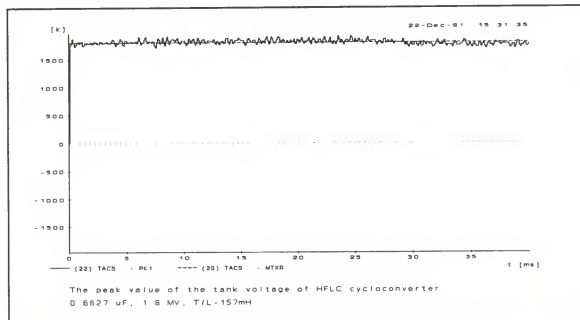


Fig. 2.11 The peak value of the tank voltage, V_t , of HFLC cycloconverter with 2.0 μF capacitance for the tank circuit in steady-state operation.

2.4 Inductive Filtering

The harmonic components of the synthesized line voltage were described by equation (2.6). The harmonic components of the line current can be expressed as

$$I_{Ln} = \frac{8V_p}{3\pi^2 n^2 \omega L_d} \left(1 + \cos\left(\frac{n\pi}{3}\right)\right) \quad (2.28)$$

Equation (2.28) shows that the harmonics in current can be suppressed by the line inductance, L_d . A less than 5% total harmonic distortion (THD) up to 21st harmonic is

generally accepted in an ac power system. The THD of the line current is written as

$$THD = \sqrt{\sum_{n=3}^{n=21} I_{Ln}^2} \cdot \frac{100}{I_{L1}} \quad (2.29)$$

From equation (2.6), (2.28) and (2.29), the transmission line inductance for the 5% THD can be expressed as

$$L_d = 0.375 \frac{V_\varphi}{\omega I_L} \quad (2.30)$$

Therefore in the case that the transmission line inductance is smaller than the inductance of equation (2.30), the HFLC ac power system needs inductive filtering. The required inductive filter L_f is obtained as

$$L_f = L_d - L_l \quad (2.31)$$

where L_l is the transmission line inductance and L_f guarantees the less than 5% THD of the line current. Fig. 2.12 shows the line current synthesized by the HFLC with 157 mH transmission line inductance. Fig. 2.13 shows the line current synthesized by the HFLC with 400 mH transmission line inductance. Harmonic components in the line current were suppressed much more in Fig. 2.13 than in Fig. 2.12.

2.5 Switching Device and Commutation Method

Switching devices with the proper power rating and the proper switching speed are the most important components needed to realize the HFLC as a FACTS element. An important parameter to be considered, when evaluating the HFLC, is power

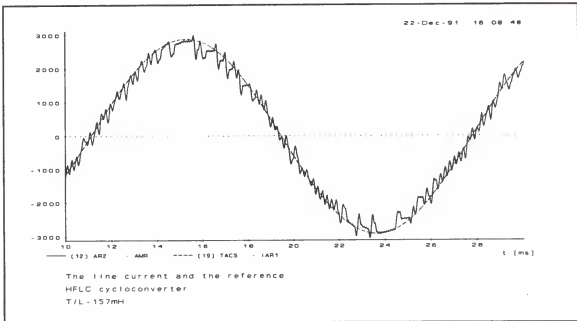


Fig. 2.12 The line current of HFLC cycloconverter with 157 mH T/L inductance.
The peak value of tank voltage is 1.8 MV.

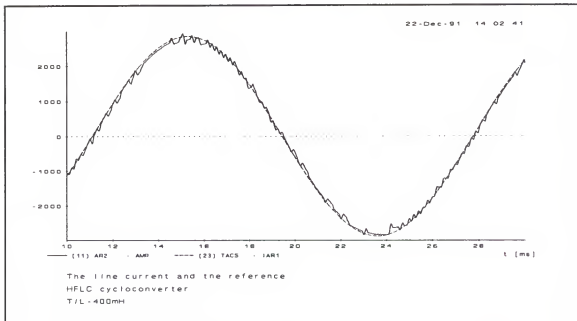


Fig. 2.13 The line current of HFLC cycloconverter with 400 mH T/L inductance.
The peak value of tank voltage is 1.8 MV.

conditioning loss. The majority of the loss in power conditioning occurs in the switching devices. Therefore, the capability of the switching devices influences the total efficiency of the HFLC.

The detailed switch structure for the HFLC was shown in Fig. 2.1. The switches consist of semiconductor switching devices and the snubber circuits. A small series inductance, a parallel capacitance and a resistor comprise the snubber circuit which limits high dv/dt and di/dt in order to protect the switch from turn-on and turn-off overvoltage and turn-on current. In the HFLC operation, the snubber circuit should be designed carefully because it also influences the efficiency and size of the converter, cooling requirement, and cost. Because the power flow can be in either direction, the HFLC needs the two anti-parallel switching devices which must have bidirectional blocking capability and bidirectional current capability. The other desirable characteristics are short switching and recovery times, a high di/dt capability, low stray inductance, high efficiency, small gate drive requirement and high power handling capability .

Table 2.1 shows the candidates of the switching device for the HFLC application. Gate-turn-off devices have self-commutating ability. Zero voltage switching can be achieved by the self-commutated switching device because it is turned off by the gate pulse instead of the tank voltage.

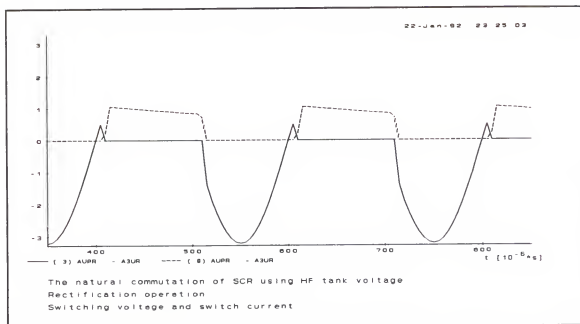
From Table 2.1, the conventional thyristor remains to be a candidate for high power applications. Thyristors can be turned off by the natural commutation. As the tank voltage changes the polarity every half cycle, the natural commutation of thyristor in the HFLC can be achieved. Because only the positive forward voltage can turn on the

Table 2.1 The candidates of the switching device for HFLC application [6].

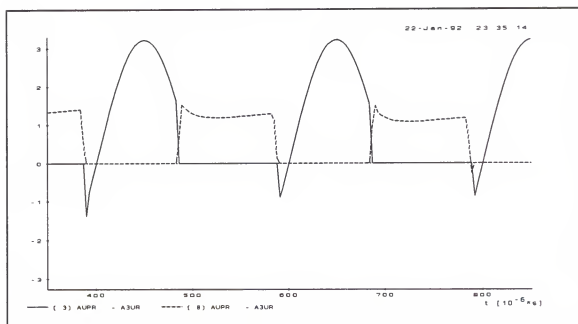
	BT	MOSFET	SIT	FCT	GTO	SCR
Maximum switching speed	200 KHz	25 MHz	50 MHz	20 KHz	20 KHz	50 KHz
Normal State	Off	On or Off	On or Off	On	Off	Off
Maximum forward current	400 A	100 A	100 A	500 A	2500 A	5000 A
Forward blocking voltage	50 - 1400 V	50 - 1000 V	50 - 1000 V		800 - 4500 V	600 - 5000 V
Reverse blocking voltage	50 V	0 V	0 V	500 - 2500 V	200 V	0 - 5000 V
Gate turn-off Capability	Yes	Yes	Yes	Yes	Yes	No
Gate-drive power	High	Low	Low	Medium	Medium	Low

thyristor and the reverse current can turn off the thyristors, the appropriate polarity of the tank voltage should be applied to the thyristor for a four quadrant operation.

To turn on the incoming thyristors and turn off the outgoing conducting thyristors in four quadrant operation, two kinds of firing are applied to the thyristor. One is the delayed firing and the other is the advanced firing [20, 34]. In the rectification operation, the power flow is from the tank circuit to the 60 Hz ac power system. It needs delayed firing of the thyristor. In the inversion operation, the power flow is from the 60 Hz AC system to the tank circuit. It needs an advanced firing. Fig. 2.14 shows the switching voltage and the switching current for natural commutation of the HFLC. The angle of



(a)



(b)

Fig. 2.14. The switching voltage and the switching current of high frequency link converter using natural commutation; the rectification operation (a), the inversion operation (b).

advanced firing is proportional to I_i and $V_i(t)$. The advanced ignition angle should be big enough to turn off the outgoing thyristors. Therefore the switching frequency of the inversion operation is limited by the available turn-off time of the thyristor and the operating condition. The inversion operation of HFLC increases the distortion in the synthesized output and the switching losses of the HFLC, when the system power factor is poor [34].

Because the detailed switching models have a very short time constant [11], logic-controlled ideal switches are used for the full-scale EMPT simulation study of the HFLC operation in an ac power transmission system.

CHAPTER 3

TOPOLOGIES OF VARIOUS HIGH FREQUENCY LINK CONVERTERS

The high frequency link converter (HFLC) is able to control power flow in an ac transmission system via changing the magnitude of output voltage and shifting the phase of line voltage. Its ability to control power flow depends on its topology. The HFLC has four applications based on the topologies of HFLCs in an ac power system: (1) the general-purpose, parallel-connected, multi-function ac-to-ac HFLC cycloconverter (HFLC cycloconverter), (2) HFLC series compensator, (3) HFLC phase shifter, and (4) HFLC shunt compensator. In this chapter, these four basic high frequency link converters (HFLCs) are briefly explained as power flow controllers. The explanation of each HFLC is focused on its basic operation in a utility environment. The four circuits are able to play their role as the power flow controller of an ac power transmission system, so they achieve accurate and fast control, increased transmittable power, increased stability margin, and damping effects. The characteristics of each HFLC is compared to the characteristics of conventional circuits.

3.1 HFLC Cycloconverter

Fig. 3.1 shows the detailed multi-function HFLC cycloconverter in an ac power system. A HFLC cycloconverter has 12 bidirectional switching devices with reverse

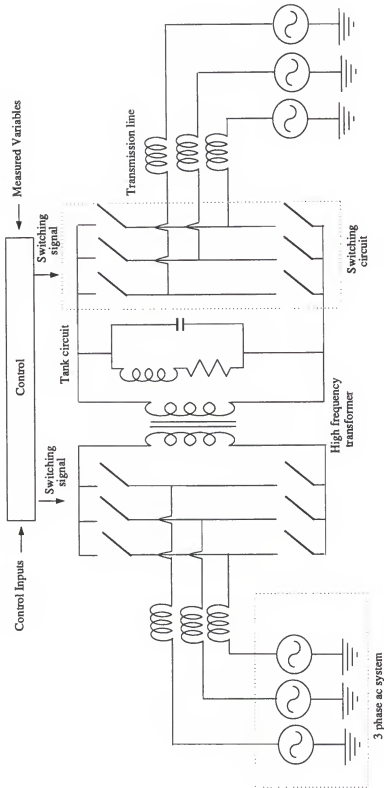


Fig. 3.1 Multi-function HFLC cycloconverter in ac power system.

blocking capability, a single ungrounded tank circuit, an optional high frequency transformer, and a controller. The transmission line in Fig. 3.1 provides the inductive filtering of the line current. The resonant tank is connected in parallel (line-to-line) with both sides of the power network through the conducting switching devices. The controller produces switching patterns in which three switching devices per bridge (two upper and one lower or vice-verse) are allowed to conduct, so the desired positive or negative tank voltage is placed across the appropriate network phase. Since the controller does not allow two switching devices on the same bridge to conduct simultaneously, the short circuit protection of the ac power system at the terminal of the HFLC cycloconverter is guaranteed.

Fig. 3.2 shows a simple ac power system with an ideal HFLC cycloconverter. The HFLC cycloconverter is installed at the midpoint of the transmission line. Fig. 3.3 shows the phasor diagram corresponding to Fig. 3.2. In the simple ac system, the real power flow, P_1 , induced by the HFLC cycloconverter is

$$P_1 = \frac{2V_1\Delta V_1\sin(\delta - \alpha_1)}{X} \quad (3.1)$$

The reactive power flow, Q_1 , supplied by system 1 is

$$Q_1 = \frac{2(V_1^2 - V_1\Delta V_1\cos(\delta - \alpha_1))}{X} \quad (3.2)$$

The converter output voltage, ΔV_1 in equation (3.1) is applied directly to the line voltage, V_1 , of the 60 Hz ac system. Therefore the system-level converter output voltages, ΔV_1 or ΔV_2 , are synthesized from the tank voltage at an arbitrary magnitude

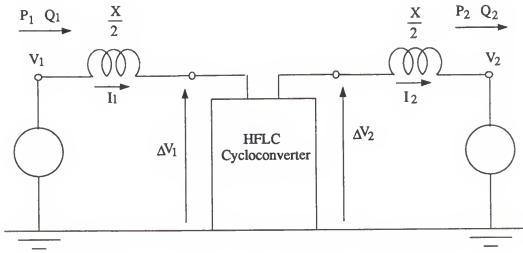


Fig. 3.2 Simple ac power system with HFLC cycloconverter

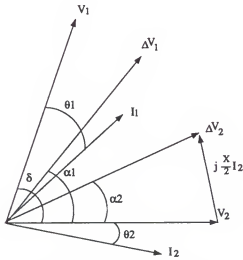


Fig. 3.3 Phasor diagram of the simple ac power system with HFLC cycloconverter.

and phase angle by the PDM controller which makes possible full control of system currents or real and reactive power on each side of the converter. Equation (3.1) shows that the HFLC cycloconverter transmits arbitrary real power between system 1 and system 2 even though the phase angle difference, δ , of the bus voltages between system 1 and system 2 is equal to zero. Although fully controllable, P_1 flowing into the HFLC cycloconverter must be equal to P_2 flowing out from the HFLC cycloconverter plus internal converter losses because the HFLC cycloconverter can not supply the real power to the ac system. For the ideal tank circuit in Fig. 3.2,

$$P_1 = P_2 \quad (3.3)$$

If it is assumed that V_1 equals V_2 , then

$$\Delta V_1 \sin(\delta - \alpha_1) = \Delta V_2 \sin \alpha_2 \quad (3.4)$$

Equation (3.4) shows that the HFLC cycloconverter has two controllable variables ΔV_1 and α_1 in each side of the real power equation. Therefore Q_1 in equation (3.2) is completely arbitrary. It means that the HFLC cycloconverter can supply or absorb reactive power to/from either or both sides of the network. This makes the HFLC cycloconverter more attractive than conventional back-to-back HVDC converters, which always consume reactive power. Equation (3.1) also shows that the installation of the HFLC cycloconverter in ac power system increases the maximum transmittable power of an ac power system.

The main disadvantage of this HFLC cycloconverter is that the tank voltage V_t must be maintained at the transmission system line voltages, V_1 or V_2 to provide full

control over the network currents. This drives up HFLC costs, since both the tank circuit and the converter switches must be rated at high transmission-level voltages.

3.2 HFLC Series Compensator

Fig. 3.4 shows the detailed topology of the series-connected HFLC continuous series compensator. The HFLC series compensator has six bidirectional switching devices with reverse blocking capability, a single ungrounded tank circuit, a 60 Hz series-connected transformer and a controller. The inductive filter in Fig 3.4 is optional. This converter circuit operates internally much the same as the HFLC cycloconverter in Fig. 3.1 except that it has only one output voltage which is placed in series with the transmission line through a series-connected transformer. The controller produces similar switching patterns to the HFLC cycloconverter. However, there can be no real power supply to or from the HFLC series compensator, since the circuit is one-sided. Therefore, the converter output voltage must be synthesized 90° out of phase with the transmission line current, in order to prevent power flow to or from the converter. Reactive flow to/from the converter is arbitrary and can be either direction, so this form of the HFLC becomes a continuously-controlled series compensator which can act as a variable series-connected capacitor or reactor.

Fig. 3.5 shows a simplified ac power system with a HFLC series compensator. The HFLC series compensator is installed at the midpoint of the transmission line. Fig. 3.6 shows the phasor diagram corresponding to Fig. 3.5. The magnitude of the converter output voltage ΔV is controlled to produce the desired amount of series compensation.

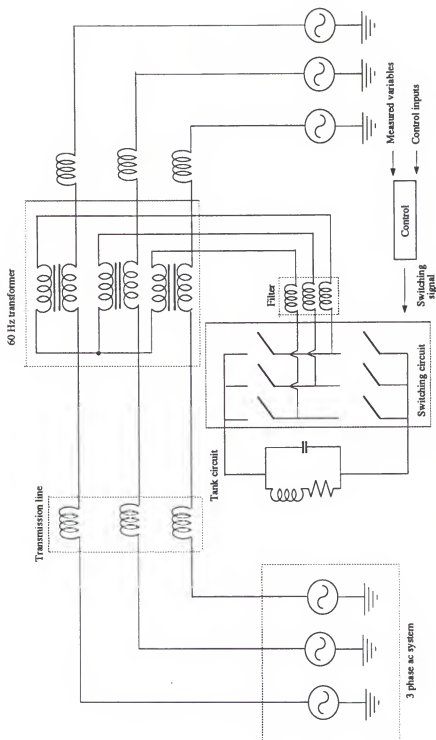


Fig. 3.4 HFLC series compensator in ac power system.

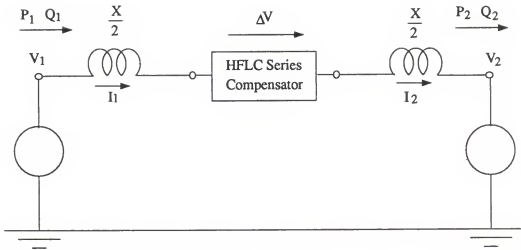


Fig. 3.5 Simple ac power system with HFLC series compensator.

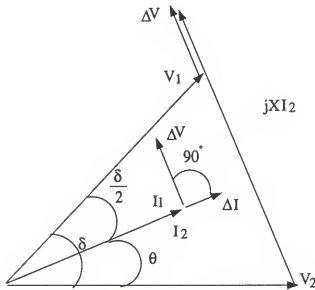


Fig. 3.6 Phasor diagram of the simple ac power system with HFLC series compensator.

The real and reactive power flows of the HFLC series compensator in Fig. 3.5 are described as

$$P_1 = \frac{V_1 V_2 \sin \delta}{X} + \frac{V_1 \Delta V}{X} \cos \frac{\delta}{2} \quad (3.5)$$

$$Q_1 = \frac{V_1^2 - V_1 V_2 \cos \delta}{X} + \frac{V_1 \Delta V}{X} \sin \frac{\delta}{2} \quad (3.6)$$

Equation (3.5) shows that the HFLC series compensator increases the transmittable power of the ac power system, which increases the stability margin of the ac power system. Equation (3.5) also explains how the HFLC series compensator produces the real power flow even at 0° power angle with the expense of a substantial reactive power of the tank circuit. The phase angle of the output voltage is also controlled in the neighborhood of 90° , in order to maintain a constant tank voltage. In steady-state, the phase angle is slightly less than 90° to allow for a small amount of energy flow into the tank, in order to compensate for circuit losses.

In a conventional series capacitive compensator, the line impedance is reduced by inserting capacitance. The increased power flow from system 1 is written as

$$P_1 = \frac{V_1 V_2 \sin \delta}{X - X_c} \quad (3.7)$$

where X_c is the reactance of the compensating capacitor in series with the transmission line. X_c has discrete characteristics. X_c also produces a subharmonic resonance frequency, f_c , combined with the line impedance. The frequency f_c is written as

$$f_e = f \sqrt{\frac{X_c}{X}} \quad (3.8)$$

where f is the power frequency of the ac power system. The frequency, f_e , may initiate the subsynchronous resonance (SSR) [25]. However, the HFLC series compensator is considered a continuous voltage source generated by the energy stored in the tank circuit. Therefore, the compensation is continuous at any operating condition and it does not initiate the SSR problem. Another advantage of the HFLC series compensator is that the tank voltage, V_t , is much smaller than the tank voltage of the HFLC cycloconverter, because the tank circuit is placed in series with the transmission line.

3.3 HFLC Phase Shifter

Fig. 3.7 shows the detailed series-connected HFLC continuous phase shifter. The HFLC phase shifter has 12 bidirectional switching devices with reverse blocking capability, a single ungrounded tank circuit, a 60 Hz series-connected transformers, a 60 Hz shunt-connected transformer, inductive filters, and a controller. Six of the twelve switching devices construct an input converter. Inductive filters in the input converter must be included in order to connect the tank circuit to the line-to-line voltage. This converter circuit operates internally much the same as the HFLC cycloconverter and the HFLC series compensator. It is similar to the HFLC series compensator in that the converter output voltage is injected into the transmission system through the series-connected transformer. It is also similar to the parallel-connected HFLC cycloconverter because there can be a real power flow through the HFLC phase shifter due to the input

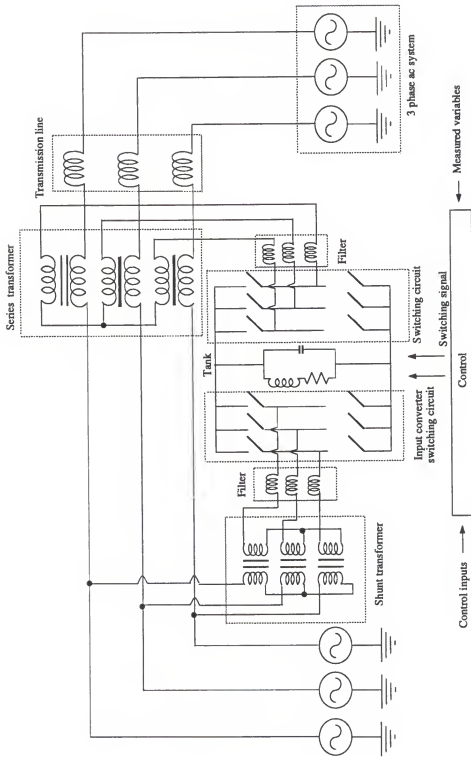


Fig. 3.7 HFCL phase shifter in ac power system.

converter which is connected to the tank circuit through a step down shunt transformer and the inductive filter. Therefore, it is more flexible than the series compensator, since it can supply a series voltage output with an arbitrary phase angle relative to the transmission line current.

Fig. 3.8 shows a simplified ac power system with the HFLC phase shifter. Fig. 3.9 shows the phasor diagram corresponding to Fig. 3.8. The real and reactive power due to the HFLC phase shifter is written as

$$P_2 = \frac{V_1 V_2 \sin \delta}{X} + \frac{V_2 \Delta V}{X} \sin \alpha \quad (3.9)$$

$$Q_2 = \frac{V_1 V_2 \cos \delta - V_2^2}{X} + \frac{V_2 \Delta V}{X} \cos \alpha \quad (3.10)$$

Equation (3.9) shows that HFLC phase shifter can transmit real power at any power angle, δ , and the HFLC phase shifter can increase or decrease the transmitted real power at any power angle, δ . It also shows that the maximum transmittable power is increased at the expense of the reactive power of the tank circuit. Therefore the HFLC phase shifter provides damping effects and increases the stability margin of the ac power system. The power flow due to a conventional phase shifter in a simple ac power system of Fig. 3.8 is written as

$$P_2 = \frac{V_1 V_2}{X} \sin(\delta - \alpha) \quad (3.11)$$

where α is the phase shifting angle determined by the conventional phase shifter. When the phase difference between V_1 and V_2 in Fig. 3.8 is near to 90° , equation (3.9) shows

that the HFLC phase shifter can force the ac transmission system to transmit the maximum power via controlling α and ΔV . However, equation (3.11) shows that the conventional phase shifter can not increase the maximum transmittable power of the uncompensated transmission line system because the conventional phase shifter changes only the angle, α . The conventional phase shifter must be located near a generator because the reactive power is supplied by the generator, but the HFLC phase shifter can be arbitrarily located.

The real and reactive power flows of the input converter are

$$P_{in} = \frac{V_{in} I_{in}}{2} \cos \theta_{in} \quad (3.12)$$

$$Q_{in} = \frac{V_{in} I_{in}}{2} \sin \theta_{in} \quad (3.13)$$

The input voltage of the input converter of the HFLC phase shifter, V_{in} , has the same magnitude as the output voltage, ΔV . The ΔV is usually small compared to the system line voltage, V_l ; therefore the HFLC phase shifter needs a step-down transformer. The input filter is required to suppress the harmonic components similar to the HFLC cycloconverter.

3.4 HFLC Shunt Compensator

Fig. 3.10 shows the detailed topology of the shunt-connected HFLC continuous static VAR compensator. HFLC shunt compensator is comprised of six bidirectional switching devices with reverse blocking capability, a single ungrounded tank circuit, an

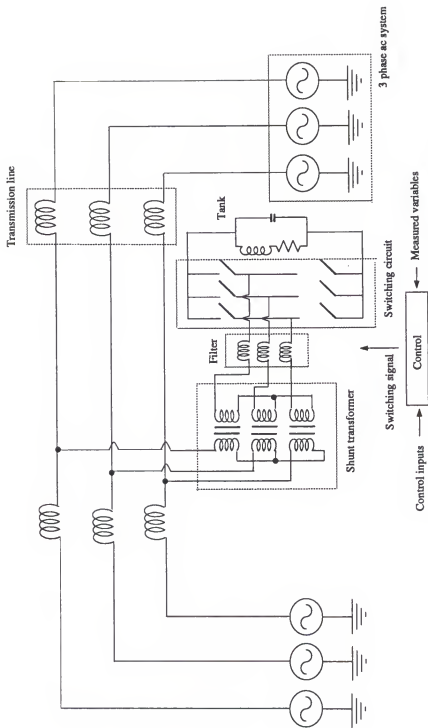


Fig. 3.10 HFLC shunt compensator in ac power system.

optional 60 Hz shunt-connected transformer, inductive filters, and a controller. Fig. 3.11 shows a simplified ac power system with a HFLC shunt compensator. Inductive filters must be included to suppress the harmonic components in the output current, I_c . This converter circuit operates internally much the same as the HFLC cycloconverter and the HFLC series compensator. It is similar to HFLC cycloconverter in that the converter output voltage is applied directly to the line voltage, so the system-level voltage is synthesized from the tank voltage. It is also similar to HFLC series compensator in that it has only one output voltage which is placed in shunt with the transmission line through the optional 60 Hz shunt-connected transformer. Switching patterns similar to the series HFLC compensator are used here to produce a balanced set of three-phase converter output voltages. In this case, there can also be no real power supply to or from the HFLC shunt compensator since the circuit is one-sided like the HFLC series compensator.

Fig. 3.12 shows the phasor diagram corresponding to Fig. 3.11. The converter output voltage, ΔV , must be synthesized in phase with the transmission line voltage, V_M , in order to prevent real power flow to or from the converter. The magnitude of the HFLC output voltage, ΔV , is controlled to produce the desired amount of shunt compensation. When $\Delta V = V_M$, the HFLC shunt compensator draws no current. However, when $\Delta V > V_M$, the current drawn by the HFLC shunt compensator via the filter inductance and the optional 60 Hz shunt transformer is purely capacitive. Similarly, when $\Delta V < V_M$, the current drawn by the HFLC becomes inductive. Thus, by controlling the output voltage of the HFLC, the reactive power can be varied

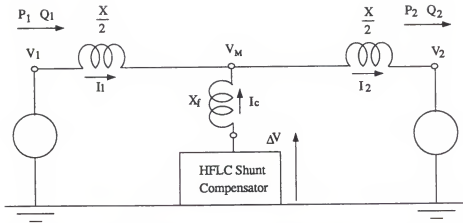


Fig. 3.11 Simple ac power system with HFLC shunt compensator.

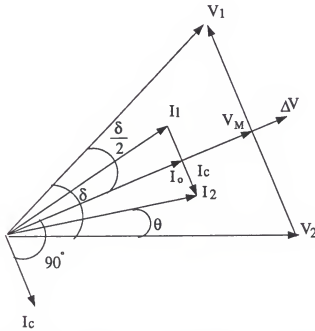


Fig. 3.12 Phasor diagram of the simple ac power system with HFLC shunt compensator.

continuously and can be in either direction, so this form of the HFLC becomes a continuously-controlled shunt static var compensator which can act as a variable shunt capacitor or reactor. The real and reactive power flows of the HFLC shunt compensator are described as

$$P_1 = \frac{V_1 V_2 \sin \delta}{X} + \frac{2 V_1 \Delta V \sin \frac{\delta}{2} - V_1 V_2 \sin \delta}{4X_f + X} \quad (3.14)$$

$$Q_1 = \frac{V_1^2 - V_1 V_2 \cos \delta}{X} - \frac{2 V_1 \Delta V \cos \frac{\delta}{2} - V_1 V_2 \cos \delta - V_1^2}{4X_f + X} \quad (3.15)$$

Equations (3.14) and (3.15) explain how the HFLC shunt compensator can generate real and reactive power flows at the expense of a substantial reactive power of the tank circuit. As a practical matter, the phase angle of the output voltage is also controlled in the neighborhood of phase angle of V_M in order to regulate a constant tank voltage. In steady-state, the phase angle of ΔV is slightly less than the phase angle of V_M to allow for a small amount of energy flow into the tank, in order to compensate for circuit losses.

A conventional shunt compensator functions as a thyristor-controlled reactive shunt impedance. Thus, the system voltage of the ac power system, V_M , and the capacitor size of the compensator decides the maximum capacitive current which in turns decides the compensation rating [14, 25]. Furthermore, the capacitive current of the conventional shunt compensator is discrete. However, the capacitive or inductive current of the HFLC shunt compensator which is decided by the voltage of the tank circuit, is

continuous at any system voltage, and thus does not have discrete characteristics. And the energy stored in the tank circuit decides the maximum compensation rating of the HFLC shunt compensator.

The main disadvantage of this HFLC shunt compensator is that the tank voltage ΔV must be maintained at the transmission system line voltages, V_M , to control network currents. This drives up HFLC costs since both the tank circuit and the converter switches must be rated at high transmission-level voltages.

CHAPTER 4

MODELING OF HIGH FREQUENCY LINK CONVERTER CONTROLLERS

The objective of high frequency link converters (HFLCs) in an ac power transmission systems is to control power flow quickly, accurately, and continuously. The power flow is controlled by changing the power system's line voltage or line current. Therefore HFLCs should be able to synthesize voltages or currents to produce any desired power flow.

The controller of HFLC has three important components; the current reference waveform pulse density modulation (CRWPDM) controller, the power flow controller, and the tank voltage controller.

Pulse Density Modulation (PDM) using zero voltage switching is able to synthesize the required low frequency waveform from high frequency pulses and to reduce the switching losses. There are several methods of implementing PDM such as Current Reference Waveform PDM (CRWPDM), Voltage Reference Waveform PDM (VRWPDM), Harmonic Elimination PDM (HEPDM), Hysteresis PDM (HPDM), etc. In this study, the HFLC uses a CRWPDM controller in order to synthesize the required output.

The power flow controller using the measured information of the ac power system generates the reference signal of the CRWPDM controller, by which the required power flow is generated. However, unless the tank voltage is maintained properly, the

CRWPDM controller can not synthesize the required output waveform. Therefore the HFLC needs a tank voltage controller. The tank voltage controller maintains the peak value of tank voltage in the proper region, and the power flow controller determines the magnitude and the phase angle of the current reference.

The overall control system is a combination of the sub-level controllers such as the CRWPDM controller, the power flow controller, and the tank voltage controller. The coordination of the sub-level controllers at a higher control level is important for proper operation of the whole HFLC ac power transmission system.

4.1 Current Reference Waveform PDM Control

Fig. 4.1 shows the current feedback scheme of the HFLC as a controller in an ac power system. The inner loop is for the CRWPDM controller. The reference signal, I_{ref} , is a sinusoidal current wave function of the desired magnitude, frequency, and phase angle. The feedback signal is a measurement of the actual line current at HFLC terminal.

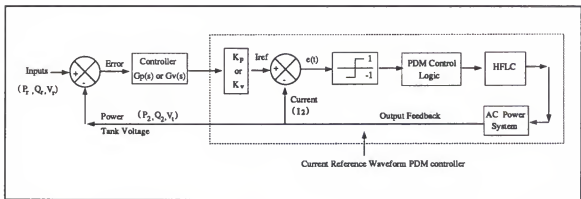


Fig. 4.1 Current feedback control scheme of HFLC as a controller in ac power system

The comparator compares the reference signal and the feedback signal and generates an error. The error between reference signal, I_{ref} , and feedback signal, I_2 , is written as

$$e(t) = I_{ref}(t) - I_2(t) \quad (4.1)$$

The error is then changed to a two-level error signal, ± 1 , at every half cycle of the resonant frequency of the tank circuit. The level of error signal depends solely on the polarity of the error, and it implies that the output current is less/greater than the reference. The PDM control logic circuit uses the polarities of error and tank voltage and it determines the switch status for the next half period of HF tank voltage at every zero crossing instant. The CRWPDM controller generates an output current which oscillates around the reference current signal. The CRWPDM controller can be considered a pure (zero hysteresis) bang-bang controller known as a delta modulator, because the CRWPDM controller does not have any proportionality to the amount of error.

Fig. 4.2 shows the reference signal and the line current synthesized by the CRWPDM controller of the HFLC cycloconverter with 1.8 MV peak tank voltage in the simplified ac power system with 2828 A peak line current and 408 KV peak line voltage. It also shows the line voltage at the terminal of the HFLC. The principle of CRWPDM is well explained in Fig. 4.2. In Fig. 4.2 it is shown that when the measured line current is less (greater) than the required current, the positive (negative) pulse of tank voltage is applied to the line to increase the line current. The synthesized line current follows the reference signal very closely. The closeness is decided by transmission line impedance, tank voltage and tank frequency. The sampling frequency of the CRWPDM controller is 10 KHz which is double the tank frequency. The peak value of tank voltage, V_b , is

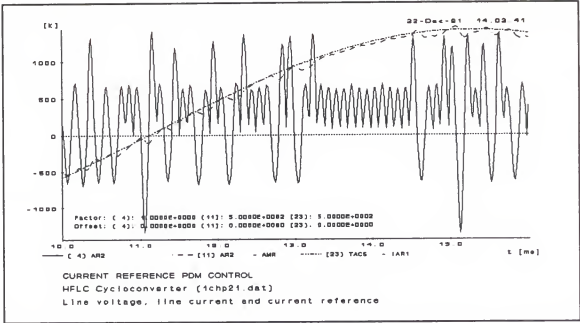


Fig. 4.2 The output voltage, the output current and the current reference of the 5 KHz HFLC cycloconverter. The output voltage was measured at the terminal of the HFLC cycloconverter.

1.8 MV. Because of the converter topology, the peak values of applied tank voltage pulse to change the level of error is one of $\pm 0.33V_b$ and $\pm 0.66V_b$, which are shown in Fig 4.2. This switching algorithm also provides short-circuit protection to HFLCs in a symmetric 3ϕ ac power system because the sum of errors in each line equals zero. Fig. 4.3 shows the response of the CRWPDM controller to a step increase of reference signal. The synthesized waveform shows that the 5 KHz CRWPDM controller responds very fast.

Several control algorithms for HFLC to synthesize the required output such as hysteresis controller [8], predictive modulator [3, 33], and delta modulator [8, 24, 41] have been proposed. However, simplified open-loop, small-signal models of HF parallel resonant converters to describe their dynamic behavior have not been developed. The

complexity involved and nonlinear characteristics of the HFLC introduce difficulties in feedback design. However, it has been shown [8] that when the frequency ratio, $2f_h/f_s$, between the switching frequency and the reference signal frequency is above 80, the delta modulator has an rms current distortion below 3%. Therefore, the 5 KHz CRWPDM controller can be considered to be an appropriate controller for an EMTF simulation study of the HFLC.

The main advantages of the CRWPDM controller to synthesize an output are the simplicity in the algorithm, the ease in implementation, and the guarantee of no short circuit at the HFLC terminal in a symmetric 3 ϕ ac power system. The CRWPDM controller can also be used as a limiter to prevent fast over-current in the ac power system.

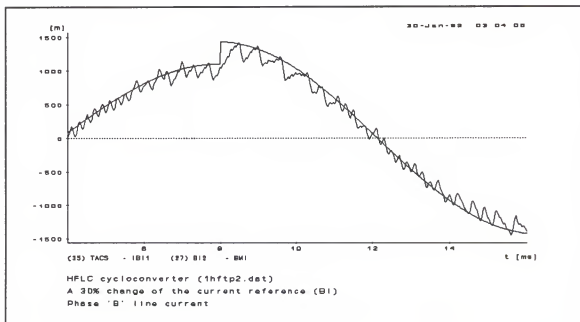


Fig. 4.3 The transient response of the CRWPDM controller to a 30% step increase in the current reference of the HFLC cycloconverter.

4.2 Comparison with Other Methods

Instead of the CRWPDM controller, a voltage reference waveform PDM (VRWPDM) controller can be used for HFLCs. A block diagram of the VRWPDM controller was shown in Fig. 2.5 of Chapter 2. Comparing Fig.4.1 to Fig. 2.5, the structure of the VRWPDM controller is the same as that of the CRWPDM controller, except for the integration, in order to synthesize output voltage. The integrator in the VRWPDM controller works as an error accumulator and low-pass smoothing function. Since the HFLC is a voltage source inverter, it is always connected to an ac power system through inductive filters. The transmission line in the ac power system provides inductive filtering to the HFLC output current. In the CRWPDM, the inductive filter works as the integrator. It has been shown that the VRWPDM controller is more sensitive to the ripple of tank voltage than the CRWPDM controller because the peak tank voltage of the HFLCs is not constant [8].

To achieve better performance of HFLCs, the current reference HPDM control was also investigated. Fig. 4.4 shows the current waveform synthesized by the HPDM controller of a HFLC cycloconverter, with a 5% upper limit and a 5 % lower limit of the line current. The current waveform shows that the current reference HPDM control does not have any advantages when compared to the CRWPDM controller. Fig. 4.5 shows the line voltage at the terminal of the HFLC cycloconverter. There are several zero voltage states of line voltage. It comes from a short circuit at the HFLC terminal. The hysteresis current controller needs an additional switching algorithm to guarantee no short circuit at HFLC terminal.

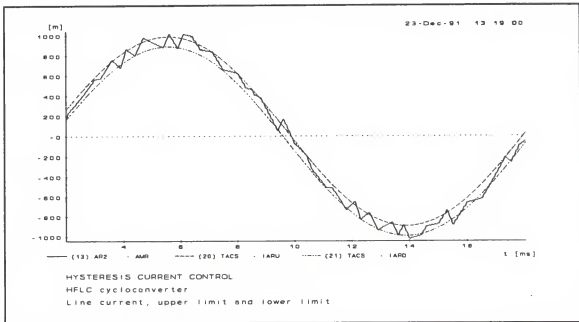


Fig. 4.4 The synthesized line current and the current reference of the 5 KHz HFLC cycloconverter. The Hysteresis PDM control was used to synthesize the line current. The bandwidth was 10% of the peak values of line current.

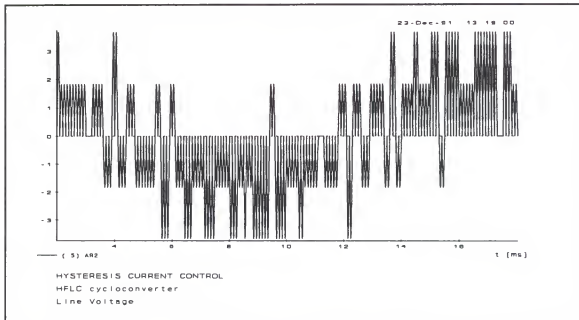


Fig. 4.5 The line voltage of the 5 KHz HFLC cycloconverter with HPDM.

The HEPDM method [5, 31] was also investigated. This method used fixed patterns to synthesize the output voltage in order to reduce harmonics in the output. Fig. 4.6 shows the current waveform synthesized by the HEPDM controller and the reference signal. Fig. 4.7 shows the line to line voltage at the HFLC terminal. The HEPDM controller needs to change the patterns to cope with various operating conditions. The patterns should be pre-computed. This control algorithm requires extensive amount of off-line computing and cannot be implemented in real-time [5]. From several simulation results, both the HEPDM controller and the HPDM controller produced more ripple in the tank voltage than the CRWPDM controller.

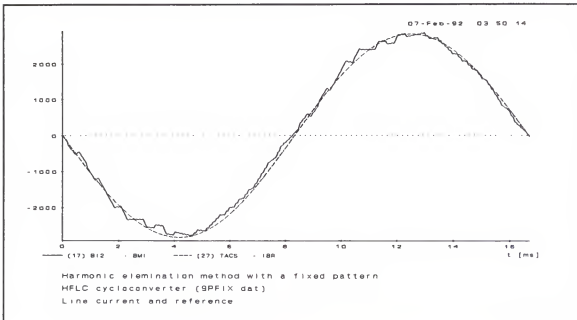


Fig. 4.6 The synthesized line current and the current reference of the 4.32 KHz HFLC cycloconverter. The Harmonic Elimination PDM control was used in order to synthesize the line current.

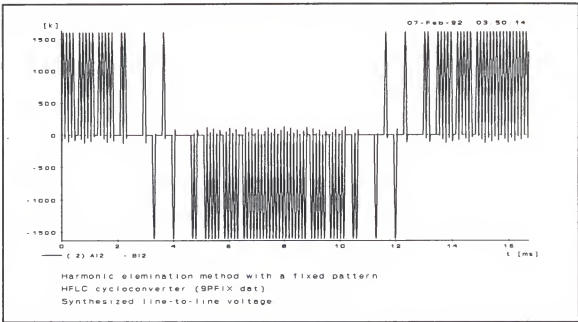


Fig. 4.7 The synthesized line-to-line voltage of the 4.32 KHz HFLC cycloconverter with HEPDM.

The total harmonic distortion (THD) up to 21st harmonic was chosen as a parameter to compare the performance of each controller. Table 4.1 shows THDs of each control method. Each method has a less than 5% THD. Thus, all of them are proper controllers for HFLCs.

Table. 4.1 The comparison of the harmonic output of PDM controllers for the HFLC cycloconverter.

	CRWPDM	VRWPDM	HEPDM	HPDM
THD of Line Current	1.96%	2.2%	2.9%	2.3%
THD of Line Voltage	13.7%	12.8%	15%	22%

4.3 Power Flow Control

The output current synthesized by the CRWPDM controller of a HFLC should be able to produce the required power flow in ac power system. The current reference of the CRWPDM controller is generated by the power flow controller using the measured information. The algorithm to measure the system information such as line voltage, line current, real power flow and reactive power flow is explained in Appendix A. In steady-state operation, the system bus voltage, V_2 , is written as

$$V_2 = V_{m2}\cos(\omega t + \phi_2) \quad (4.2)$$

where V_{m2} is the peak value of the voltage, ϕ_2 is the phase angle and the line current, I_2 , is written as

$$I_2 = I_{m2}\cos(\omega t + \phi_2 - \theta_2) \quad (4.3)$$

where I_{m2} is the peak value of the current, and θ_2 is the phase angle difference between V_2 and I_2 . The instantaneous power flow, S_2 , is written as

$$S_2 = \frac{1}{2}V_{m2}I_{m2}\cos\theta_2(1+\cos 2\omega t) + \frac{1}{2}V_{m2}I_{m2}\sin\theta_2\sin 2\omega t \quad (4.4)$$

The real and reactive power flows are then expressed as

$$P_2 = \frac{1}{2}V_{m2}I_{m2}\cos\theta_2 \quad (4.5)$$

$$Q_2 = \frac{1}{2}V_{m2}I_{m2}\sin\theta_2 \quad (4.6)$$

Equations (4.5) and (4.6) mean that the real and reactive power flows can be controlled by changing I_{m2} , and/or θ_2 arbitrarily.

The power flow controller provides I_{m2} , or/and θ_2 , to the CRWPDM controller, corresponding to the required P_2 and Q_2 at the terminals of the HFLC. The CRWPDM controller synthesizes the magnitude and phase of the output current at the terminals of the HFLC. This allows the HFLC in the ac power system to control the power flow with a lagging or leading power factor.

Fig. 4.8 (a) shows the constant real power control and Fig. 4.8 (b) shows the constant reactive power control. In Fig. 4.8 (a), the following equation can be derived:

$$G_2 = I_a \cos \theta_a = I_b \cos \theta_b = I_c \cos \theta_c \quad (4.7)$$

where G_2 is determined by the required power P_2 of system 2.

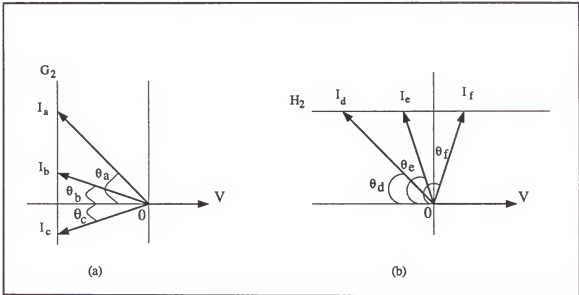


Fig. 4.8 The current and voltage vectors for the real and reactive power flow controls; constant real power control (a), constant reactive power control (b).

While the real power flow, P_2 , is kept at a constant value, the reactive power, Q_2 , can be regulated by the following:

$$P_2 = \frac{1}{2} V_{m2} G_2 \quad (4.8)$$

$$Q_2 = \frac{1}{2} V_{m2} G_2 \tan \theta_2 \quad (4.9)$$

The following equation can also be derived from Fig. 4.8 (b):

$$H_2 = I_d \sin \theta_d = I_e \sin \theta_e = I_f \sin \theta_f \quad (4.10)$$

where H_2 is a constant determined by the desired reactive power, Q_2 , of system 2. The real power, P_2 , can be regulated while the reactive power, Q_2 , is maintained at a constant value as shown by the following:

$$P_2 = \frac{1}{2} V_{m2} H_2 \cot \theta_2 \quad (4.11)$$

$$Q_2 = \frac{1}{2} V_{m2} H_2 \quad (4.12)$$

From equations (4.8), (4.9), (4.11) and (4.12), P_2 and Q_2 can be controlled independently. However, the actual independent power control of HFLCs is determined by the topology of the HFLC and the tank voltage.

The power flow control of the HFLC during a transient is explained in Fig. 4.1. The real power, P_2 , and the reactive power, Q_2 , are measured as feedback signals for the controller. P_2 and Q_2 are not constant because the operating condition of the ac power system always changes. These measured signals are compared to the input signals, P_r ,

and Q_r . The power flow controller generates the new current reference, I_{ref} , as the input signal of the CRWPDM controller. The new current reference reduces the error between the input signals, and the measured signals. Therefore the characteristic of the power flow controller determines the characteristics of the power flow in an ac power system.

To design the power flow controller, it is assumed that the new and old equilibrium states of the ac power system are nearly equal. During the transition between the states, the ac power system behavior can be described by linearized system equations. The simple ac power system of this study is described as a unity transfer function system.

An appropriate model for the study of HFLC's dynamic characteristics has not been available because of the nonlinear behavior of HFLC and the complexity. In section 4.1, it was shown that the output waveform in the HFLC was synthesized very fast. This means that the response speed of a 5 KHz HFLC is very fast compared to that of the ac power system. Therefore the combined system of the CRWPDM controller and HFLC in Fig. 4.1 is also considered as a unity transfer function system.

Then the transient characteristics of the power flow controller decide the power flow characteristics of the ac power system with the HFLC, so the power flow controller should be designed carefully. The controller is designed as a second order transfer function system, because a higher order transfer function system can be approximated as a second order transfer function system and because the steady state error of the second order system to a step change is zero.

In Fig. 4.1, $G_p(s)$ on diagram may be written as

$$G_p(s) = \frac{\omega_{np}^2}{s(s + 2\zeta_p \omega_{np})} \quad (4.13)$$

where ζ_p is the damping factor and ω_{np} is the undamped natural frequency. The closed loop transfer function of power flow loop in Fig. 4.1 is given by

$$\frac{P_2}{P_r} = \frac{\omega_{np}^2}{s^2 + 2\zeta_p \omega_{np} s + \omega_{np}^2} \quad (4.14)$$

P_2 equals P_r in steady-state. The parameters ω_{np} and ζ_p are very important for characterizing a system's response. The time for the system to damp out all transients is commonly called the settling time, t_{sp} . In practice, the transient is assumed to be over when the error is reduced below some minimum value. Typically, the minimum level is set at 2% of the final value. Therefore, the settling time is given by

$$t_{sp} = \frac{4}{\zeta_p \omega_{np}} \quad (4.15)$$

However, it is possible that the controller may not be able to properly control the power flow if the disturbance is too big because the controller, $G_p(s)$, was designed with the small disturbance assumption.

The proportional constant, K_p , in Fig. 4.1 connects the power flow controller to the CRWPDM controller, and K_p depends on the topology of the HFLC. For a small disturbance in the simple ac power system, the linearization of the power equations (4.5) and (4.6) gives

$$\begin{bmatrix} \Delta P_2 \\ \Delta Q_2 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} V_{m2} \cos \theta_2 & -V_{m2} I_{m2} \sin \theta_2 \\ V_{m2} \sin \theta_2 & V_{m2} I_{m2} \cos \theta_2 \end{bmatrix} \begin{bmatrix} \Delta I_{m2} \\ \Delta \theta_2 \end{bmatrix} \quad (4.16)$$

It is transformed to

$$\begin{bmatrix} \Delta I_{m2} \\ \Delta \theta_2 \end{bmatrix} = \begin{bmatrix} \frac{2 \cos \theta_2}{V_{m2}} & \frac{2 \sin \theta_2}{V_{m2}} \\ -\frac{2 \sin \theta_2}{V_{m2} I_{m2}} & \frac{2 \cos \theta_2}{V_{m2} I_{m2}} \end{bmatrix} \begin{bmatrix} \Delta P_2 \\ \Delta Q_2 \end{bmatrix} \quad (4.17)$$

Thus, K_p in Fig. 4.1 is written as

$$K_p = \begin{bmatrix} \frac{2 \cos \theta_2}{V_{m2}} & \frac{2 \sin \theta_2}{V_{m2}} \\ -\frac{2 \sin \theta_2}{V_{m2} I_{m2}} & \frac{2 \cos \theta_2}{V_{m2} I_{m2}} \end{bmatrix} \quad (4.18)$$

The new current reference of the CRWPDM controller, I_{ref} , is generated corresponding to the new power flow as the following:

$$I_{ref} = (I_{m2} + \Delta I_{m2}) \cos(\omega t + \phi_2 - \theta_2 - \Delta \theta_2) \quad (4.19)$$

where ΔI_{m2} and $\Delta \theta_2$ is zero at steady state, and I_{m2} and θ_2 are generated by the equations (4.5) and (4.6).

4.3.1 HFLC Cycloconverter

The power flow controller of the HFLC cycloconverter generates two current references $I_{ref,1}$ and $I_{ref,2}$ for each side of HFLC cycloconverter. The real power flow

equation for the simplified ac power system with the HFLC cycloconverter in Fig. 3.2 is written as

$$P_1 = P_2 + P_t \quad (4.20)$$

where P_t is the power dissipated in the tank circuit. In an ideal HFLC case, P_t can be neglected. As long as the equation (4.20) is satisfied, the line currents I_1 and I_2 may have arbitrary magnitudes and phase angles, relative to the system voltages. This means the reactive power flow on each side can be controlled in the same or opposite directions, with an arbitrary magnitude, subject only to the HFLC rating limits.

In transient operation, equation (4.18) is used for gains $K_{p,1}$ and $K_{p,2}$. Therefore, new current references $I_{ref,1}$ and $I_{ref,2}$ have the same forms as equation (4.19). In order to keep the reactive power of system 2 constant, ΔQ_2 is set to zero in equation (4.17). The real power can be kept constant during a transient if ΔP_2 is set as zero in equation (4.17).

4.3.2 HFLC Series Compensator

Real power flow equation in the simplified ac power system with the HFLC series compensator in Fig. 3.5 is written the same as equation (4.20). P_t is assumed small enough to be neglected. In steady-state operation, P_1 should equal P_2 . There can be no net real power injected or absorbed by the HFLC series compensator, so the angle between the compensator voltage, ΔV , and the line current I_1 must be $\pm 90^\circ$.

The HFLC series compensator uses a single current reference to control power flow, since it is series-connected in the transmission line. The line current in steady-state can therefore be varied in magnitude but not in phase. It means that the HFLC series

compensator can increase the power flow in the capacitive mode which has the decreased equivalent line reactance or decrease the power flow in the inductive mode which increases equivalent line reactance. However, it can not decouple the real power control from the reactive power control. The phase angle of current reference would be chosen based on the relative magnitude and phase of the system voltages.

For the transient mode, $\Delta\theta$ in equation (4.16) is assumed to be zero or small enough to be neglected because the line current I_l can not have an arbitrary phase angle in the series case. Therefore, from equation (4.18), the gain K_p is obtained as

$$K_p = \begin{bmatrix} \frac{2}{V_{m2}\cos\theta_2}, & 0 \\ 0, & 0 \end{bmatrix} \quad (4.21)$$

the new current reference of the HFLC series compensator is written as

$$I_{ref} = (I_{m2} + \Delta I_{m2}) \cos(\omega t + \phi_2 - \theta_2) \quad (4.22)$$

where I_{m2} and θ_2 are determined by equations (4.5) and (4.6).

4.3.2 HFLC Phase Shifter

The HFLC phase shifter also uses a single current reference to control power flow, since it is series-connected in the transmission line. In the HFLC phase shifter, however, real power can be injected or absorbed by the compensator, so the phase angle θ between the compensator voltage, ΔV , and the line current I_l is arbitrary. In Fig. 3.8, the power flow equation in steady-state is written as

$$P_2 + P_t = P_1 + P_m \quad (4.23)$$

where the real power P_m is provided by the ac power system and P_t is the real power dissipated in the tank circuit. P_t can be neglected in an ideal HFLC. P_m is assumed to be small because the receiving power P_2 is mainly supplied by P_1 . However, the single reference current can be varied in magnitude and also in phase due to P_m . Therefore, the real power control and reactive power control can be decoupled like the HFLC cycloconverter. However, since the compensator voltage is generally much smaller than the system voltage, the HFLC phase shifter will not have the same range of control obtained by the HFLC cycloconverter.

For the HFLC phase shifter, equation (4.18) is used for gain K_p in Fig. 4.1. The new current reference for the transient case is found from equation (4.19).

4.3.4 HFLC Shunt Compensator

There can be no net real power injected or absorbed by the HFLC shunt compensator, similar to the HFLC series compensator, so the angle between the compensator voltage, ΔV , and the output current I_c must be $\pm 90^\circ$. The single reference current can therefore be varied in magnitude but not in phase. The phase angle of current reference would be chosen based on the relative magnitude and phase of the system voltages. Therefore it can not accomplish the real power control decoupled from the reactive power control. However, the HFLC shunt compensator can increase the real power flow in the capacitive mode or decrease the real power flow in the inductive mode.

For the power flow controller of the HFLC shunt compensator, equation (4.21) is again used for gain K_p in Fig. 4.1. Equation (4.22) is used for the new current reference.

4.4 Tank Voltage Control

The reasons to keep the high frequency tank voltage at a proper level are:

- a) The HFLCs in the power system must be able to limit 60 Hz line current.
- b) The switching devices have to be protected from malfunction.
- c) The synthesized output should be distortion-free [12].

The steady-state power flow equation in the simplified ac power system was written as equation (4.20), where P_i makes up for the real power dissipated in the tank circuit, which is the ohmic losses in equation (2.14). When P_i is less (more) than the ohmic losses, the tank voltage decreases (increases) below (above) the desired level. The level of tank voltage should be maintained in minimum magnitude to minimize the operating cost of HFLC. The ac power system always changes its operating condition. Therefore the tank voltage should be controlled to the level which makes the HFLC work properly. Since the level of the tank voltage can be controlled by changing of the power balance between the input power and the output power, the tank voltage control can be obtained by establishing an appropriate command I_{ref} for the output currents of the HFLC.

Fig. 4.1 shows the structure of the transient tank voltage controller using a current feedback scheme. Because of the nonexistence of the appropriate model for the

study of HFLC's dynamic characteristics, the design of the tank voltage controller uses the same assumption as the power flow controller. The CRWPDM controller and the ac power system are again assumed as a unity transfer function system. The peak tank voltage V_t is measured as a feedback signal of the controller. It is compared to the input signal V_r . The tank voltage controller, $G_v(s)$, generates the new current reference I_{ref} as the input signal of the CRWPDM controller. The characteristics of $G_v(s)$ decides the characteristics of the tank voltage control loop. It should be designed carefully. In Fig. 4.1, $G_v(s)$ on diagram may be written as

$$G_v(s) = (1 + \alpha Ts) \frac{\omega_{nt}^2}{s(s + 2\zeta_t \omega_{nt})} \quad (4.24)$$

where ζ_t is the damping factor and ω_{nt} is the undamped natural frequency. The closed loop transfer function of tank voltage loop is written as

$$\frac{V_t}{V_r} = \frac{(1 + \alpha Ts) \omega_{nt}^2}{s^2 + 2\omega_{nt}(\zeta_t + \frac{\alpha T \omega_t}{2})s + \omega_{nt}^2} \quad (4.25)$$

$G_v(s)$ in equation (4.24) is the product of $G_t(s)$ and $G_c(s)$.

$$G_t(s) = \frac{\omega_{nt}^2}{s(s + 2\zeta_t \omega_{nt})} \quad (4.26)$$

$$G_c(s) = 1 + \alpha Ts \quad (4.27)$$

$G_c(s)$ predicts a large overshoot ahead of time and makes proper corrections before the overshoot occurs. It also emphasize the high frequency component in the feedback signal.

$G_c(s)$ increases the damping of the system without influencing the steady-state error of the system [21]. The tank voltage controller $G_v(s)$, which is the product of $G_i(s)$ and $G_c(s)$, shows good performance in controlling the tank voltage because it is very sensitive to the high frequency component of the power flow in ac power system.

The proportional constant, K_v , in Fig. 4.1 connects the tank voltage controller to the CRWPDM controller as follows:

$$\Delta \theta = K_v \Delta V_t \quad (4.28)$$

where K_v depends on the topology of HFLC. The tank voltage controller works only on the phase angle, θ , even though the change in the magnitude of the line current changes the real power flow to the tank circuit.

The peak energy stored in the single ungrounded tank circuit is written in terms of tank voltage and tank capacitance in equation (2.12), which gives

$$\Delta W_t = 3P_t T_t = CV_t \Delta V_t \quad (4.29)$$

where T_t is the time interval for the linearization.

The tank voltage controller of the HFLC cycloconverter uses the power flow from system 1. It is assumed that P_2 is constant. Then, the relationship between the small change of the input power and the power flowing to the tank circuit from equation (4.20) is written as

$$P_t = \Delta P_1 \quad (4.30)$$

Then by combining equation (4.16) and (4.28), the small change of the phase angle of the line current of system 1 is written as

$$\Delta \theta_1 = \frac{-2CV_t}{3V_{m1} I_{m1} \sin \theta_1 T_l} \Delta V_t \quad (4.31)$$

Both the HFLC series compensator and the HFLC shunt compensator use a single reference as the input of the CRWPDM controller. The change in the magnitude of the line current does not influence the power flow flowing to the tank circuit. Therefore, the small change of the phase angle of the line current can be used to control the tank voltage. By using the power flow equation (4.20) for the ideal HFLC in the simplified ac power system, the power flow into the tank circuit is written as

$$P_t = \frac{-(V_{m1} + V_{m2}) I_t \sin \theta}{2} \Delta \theta \quad (4.32)$$

By substituting equation (4.29) into equation (4.32),

$$\Delta \theta = \frac{-2CV_t}{3(V_{m1}+V_{m2})I_m \sin \theta T_l} \Delta V_t \quad (4.33)$$

The HFLC phase shifter uses the input converter to control tank voltage. The phase angle of input current is chosen as the control variable. Therefore, the power flow to the tank circuit is written as

$$P_t = \Delta P_{in} \quad (4.34)$$

then

$$\Delta \theta_{in} = \frac{-2CV_t}{3V_{in} I_{in} \sin \theta_{in} T_l} \Delta V_t \quad (4.35)$$

Therefore the new current reference for the CRWPDM controller, $I_{ref,1}$ is written as

$$I_{ref,1} = I_{m1} \cos(\omega t + \phi_1 - \theta_1 - \Delta\theta_1) \quad (4.36)$$

where I_{m1} and θ_1 are for the steady-state power flow operation and $\Delta\theta_1$ is zero in steady state. During a transient, $\Delta\theta_1$ controls the tank voltage level by supplying the required power to the tank circuit. The gain constant K_v which connects the tank voltage controller to the CRWPDM controller was given in equations (4.31), (4.33) and (4.35).

4.5 High-Level Control System

The high-level control system is a combination of sub-level controllers such as the CRWPDM controller, the power flow controller, the tank voltage controller, and the protector. The coordination of the sub-level controllers at a higher control level is important for proper operation of the whole HFLC power transmission system.

Fig. 4.9 shows a diagram of the controller developed for the HFLC cycloconverter. The upper and lower loop controls the real/reactive power for the ac power system and the center loop controls the tank voltage of the HFLC cycloconverter. Both control loops have two subloops (not shown) which determine the magnitude and phase angle of the respective reference currents. The upper and lower loops use feedback measurements of real and reactive power for direct comparison with power settings on each side of the converter. The center loop uses a feedback measurement of the tank voltage for comparison with a tank voltage reference, which is a derived function of the power settings. Since the tank voltage controller works on the left-side power flow, it is superimposed on the lower power flow loop which is for the left-side. Both upper and lower control loops also use a feedback measurement of the respective line current for

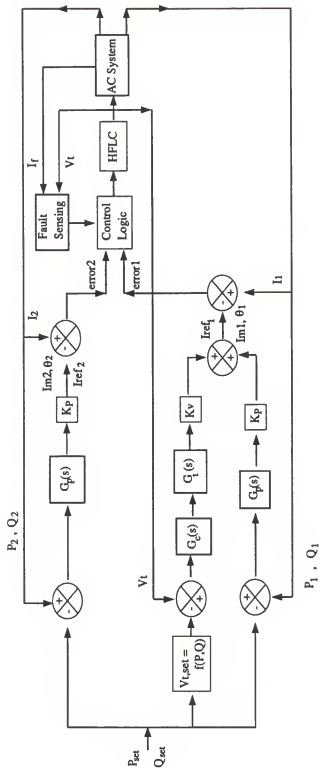


Fig. 4.9 Controller of HFLC cycloconverter.

comparison with each current reference wave generated by the controller. Fig. 4.9 also shows the fault sensing loop. The loop is initiated by high tank voltage. The control logic during the high tank voltage period dissipates the energy in the tank circuit. After the high tank voltage is cleared, a new current reference is determined by using the steady-state fault current, which is pre-calculated by the load flow. Therefore this loop can limit high fault currents in the power system. While this loop works, the power flow controller and the tank voltage controller are disabled.

Fig. 4.10 shows a diagram of the controller developed for the HFLC series compensator. The upper loop controls the real power for the system by working on the current reference magnitude I_m . In this case the reactive power cannot be controlled independently because of the steady-state requirement of a 90° phase angle between the compensator output voltage and the line current. The lower loop controls the tank voltage by working on the current phase angle. This angle is tightly controlled in the neighborhood of 90° in order to regulate the net energy flow into the tank, which in turn controls the tank voltage. The upper loop uses a feedback measurement of real power for direct comparison with the power setting. The lower loop uses a feedback measurement of the tank voltage for comparison with a tank voltage reference, which is a derived function of the power setting. The control system also uses a feedback measurement of the line current for comparison with the current reference wave generated by the controller. The fault sensing loop is shown again, which uses the same algorithm as the HFLC cycloconverter.

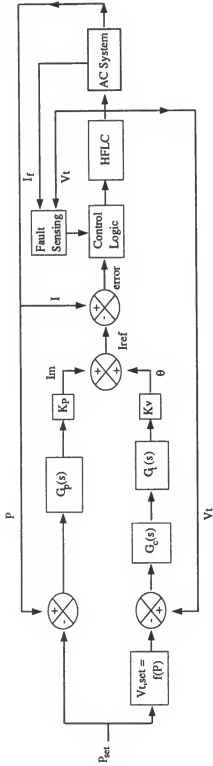


Fig. 4.10 Controller of HFLC series compensator.

Fig. 4.11 shows a diagram of the controller developed for the HFLC phase shifter. In this case, the upper loop controls the real and reactive power delivered to the right-hand system, by working on both the current reference magnitude I_m and phase angle for the converter output current. The lower loop controls the tank voltage by working on the converter input current reference. The upper loop uses a feedback measurement of real and reactive power for direct comparison with the output power setting, and the lower loop uses a feedback measurement of the tank voltage for comparison with a tank voltage reference. The control system also uses a feedback measurement of the input and line current for comparison with the current reference waves generated by the control. The fault sensing loop is shown again, using the same algorithm as the HFLC cycloconverter.

Fig. 4.12 shows a diagram of the controller developed for the HFLC shunt compensator. The upper loop controls the real power for the system by working on the current reference magnitude I_m . In this case, the reactive power cannot be controlled independently because of the steady state requirement of a 90° phase angle between the compensator output voltage and the output current. The lower loop controls the tank voltage by working on the current phase angle. This angle is tightly controlled in the neighborhood of 90° in order to regulate the net energy flow into the tank, which in turn controls the tank voltage. The upper loop uses a feedback measurement of real power for direct comparison with the power setting. The lower loop uses a feedback measurement of the tank voltage for comparison with a tank voltage reference, and the control system also uses a feedback measurement of the line current for comparison with the current

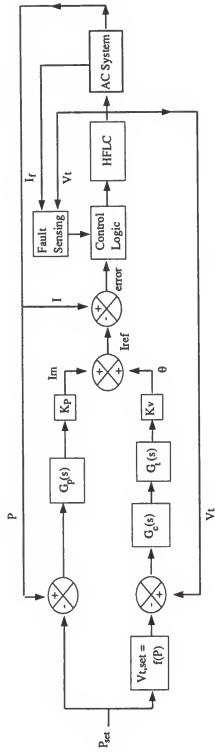


Fig. 4.12 Controller of HFLC shunt compensator.

reference wave generated by the controller. The fault sensing loop shown uses the same algorithm as the HFLC cycloconverter.

CHAPTER 5 SIMULATION AND RESULTS

In this chapter, the performance of high frequency link converters (HFLCs), designed as power flow controllers, is evaluated to determine the feasibility for improved performance of the ac power transmission system. The capabilities required as FACTS elements are

- 1) fast and accurate current control
- 2) low output distortion
- 3) increased power transmission capability
- 4) versatile control of power flow
- 5) fault current limiting and damping effects

These capabilities of HFLCs were tested singly and in combination.

The evaluation of the feasibility of the HFLC as a power flow controller was performed by computer simulation. The general purpose simulation program EMTP (Electro-Magnetic Transient Program) was used for the simulation study of HFLC circuits. EMTP is comprised of four modules: the electric network (EN), the control system (TACS), the mechanical system (MS), and the universal machine (UM) module. The interfacing of the above four modules can simulate various electric energy systems. For this research, the TACS module and the EN module are used for the simulation study of HFLCs in ac power systems.

The first step is to develop computer simulations of HFLCs and the test systems. The circuits developed are the HFLC cycloconverter, the HFLC series compensator, the HFLC phase shifter and the HFLC shunt compensator. Each of them has its own power flow controller and tank voltage controller. The EMTP simulation study includes individual representations of the switching devices and other high-frequency circuits within each HFLC, as well as the various transfer functions and signal processing elements within each HFLC control system. Because the purpose of this study is to investigate in detail the feasibility of operating HFLCs in the utility system environment, a fully-detailed, three-phase representation of a utility system was utilized in the simulation studies.

The main results of the study are a detailed technical evaluation of the HFLC concept for use as a FACTS control element. Comparisons between the four types of HFLC configurations developed were also performed. The EMTP simulation study of highly-detailed HFLC models is suitable only for relatively short-term studies because of large computing time requirements. However, much can be learned about the overall performance of HFLCs as an element in the FACTS control scheme, using EMTP. A secondary result is EMTP input data files used for the simulation of the HFLC-based test system. These may be useful in future studies of the HFLC concept.

5.1 Test AC Power Systems

In order to evaluate the performance of the HFLC as a controller in an ac power system, a simplified 3 ϕ ac power transmission system was initially used in the simulation

study. The simple test system is a 500 KV, 2000 A transmission line with a 60 [ohm] reactance. The detailed circuit diagrams combined with HFLCs were shown in Fig. 3.1, Fig. 3.4, Fig. 3.7 and Fig. 3.10. Since the simple 3 ϕ ac power system is a point-to-point system, these systems were used for the evaluation of the steady state performance, the harmonic analysis, the initial transient performance and the versatile control capabilities.

In order to evaluate the performance of HFLCs in a more complex and practical ac power system, the utility system test model was developed with close cooperation of the utility advisor at the Florida Power and Light (FP&L) Company. It models the main features of the 500 KV system that interconnects the Southern Company network with the Florida grid. Fig. 5.1 is a one line diagram showing the major buses of interest in this system. Since it is basically a radial system, the HFLC is useful mainly for increasing power flow during loss of one of the tie lines or loss of power generation in the South Florida region, and for preventing loop power flows in the FP&L system.

Fig. 5.2 is another diagram of this system which depicts in more detail the EMTP simulation model used for the short term feasibility studies of HFLCs in the Florida 500 KV network. In the EMTP simulation studies, the HFLC is placed at the Poinsett bus in the 500 KV line connecting directly to Duval, as shown in the diagram. In the EMTP simulation, each generating unit shown was modeled by an equivalent three-phase voltage and coupled impedance, as necessary to produce the actual load flow and approximate the transient performance. Transformers connecting to the 230 KV systems were modeled by three-phase equivalents as shown. The transmission lines were represented by a combination of coupled three-phase models and distributed-parameter equivalents. Line

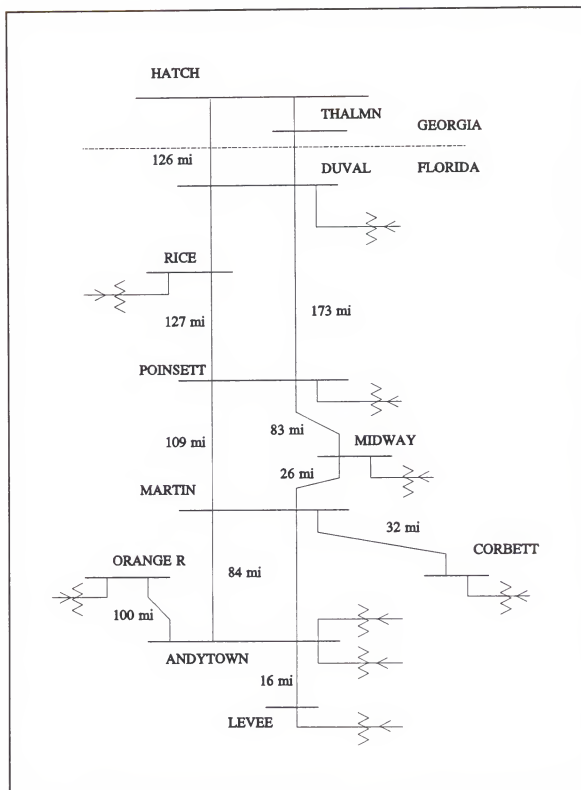


Fig. 5.1 The simplified one line diagram of FP&L 500 KV system.

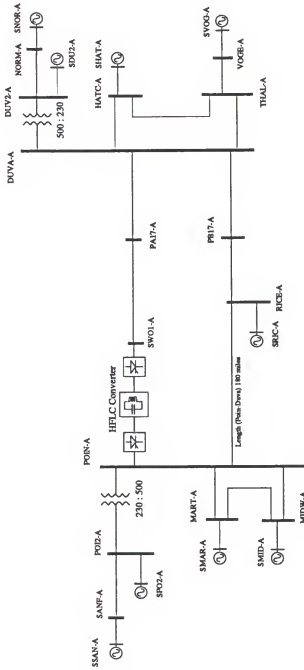


Fig. 5.2 Utility test model for EMTP simulation. This figure shows the HFLC location in FP&L system and in more detail the EMTP simulation model.

parameters were only available at 60 Hz and loads were represented as three-phase constant impedances.

A summary of the FP&L system load flow data file is given in Appendix D, which represents the base case without the HFLC connected. A sample EMTP data file for the system simulation, without the HFLC connected, is given in Appendix E. Distributed parameter line models are used exclusively in this sample EMTP file. Also shown in appendix E is part of the corresponding EMTP output file, which was used to verify the EMTP network model by comparison with the original load flow data.

5.2 Steady-State Performance of HFLCs in a Simple Test System

The steady state performance of HFLCs in a simple ac power test system was evaluated to show the feasibility of HFLCs. Fig. 5.3 through 5.6 show typical wave forms for steady-state operation of the HFLC cycloconverter. Fig 5.3 shows the tank voltage. The peak tank voltage approximately equals 1.3 MV with 80 mH inductive filters transmission line on each side of the system. The tank voltage has ripples in the peak value at every half cycle. The peak value of the tank voltage should be confined to a specific range for the proper operation of the HFLC. Fig. 5.4 and 5.5 show the unfiltered line voltage and the line-to-line voltage at the converter output terminal on the right-hand side (system 2) of the circuit. The converter voltages on the other side look similar. These unfiltered voltages clearly show the nature of the PDM-type wave although the 60 Hz fundamental voltage is masked by the high-frequency pulses. Fig 5.6 shows the transmission line current I_2 resulting from the difference in the right hand

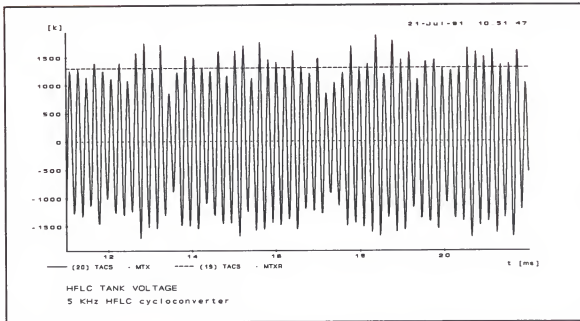


Fig. 5.3 Tank voltage and the peak value reference of the HFLC cycloconverter in the simple ac power system. The reference is 1.3 MV. The ac power system operates at the 408 KV peak line voltage and the 2828 A peak line current. The capacitance of the 5 KHz tank circuit is $0.69 \mu\text{F}$.

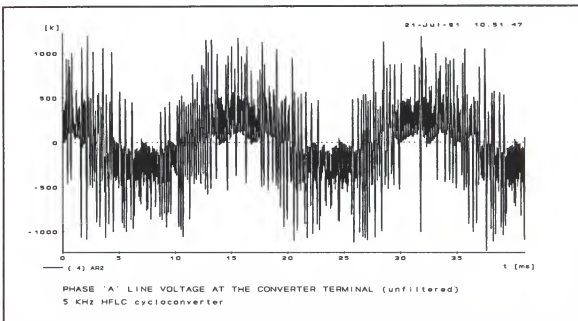


Fig. 5.4 Line voltage synthesized by the HFLC cycloconverter in the simple ac power system. The operating conditions are the same as those of Fig. 5.3. The line inductance is 157.5 mH in each side of the ac power system.

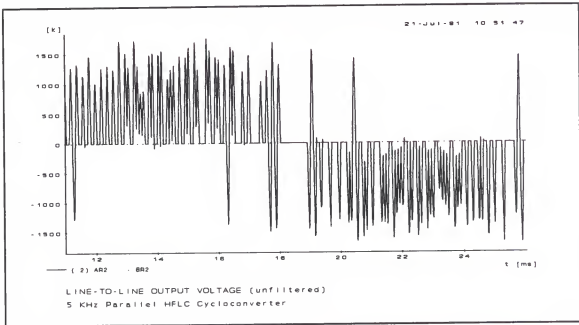


Fig. 5.5 Line-to-line voltage of the HFLC cycloconverter in the simple ac power system. The operating conditions are the same as those of Fig. 5.3.

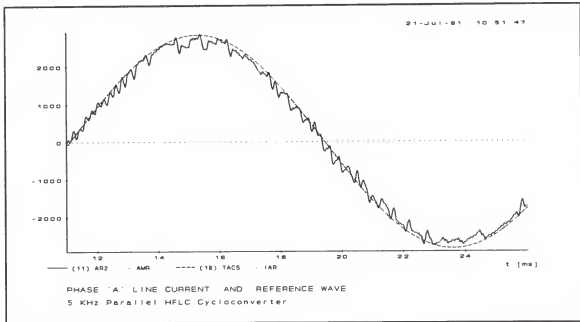


Fig. 5.6 Line current and the line current reference of the HFLC cycloconverter in the simple ac power system. The operating conditions are the same as those of Fig. 5.3.

converter output voltage ΔV_2 and system voltage V_2 . Also plotted is the reference current sent to the control system. This shows that the transmission line with small additional inductive filters performs a good share of the required filtering, as the current ripple is very small compared to the fundamental component. The results shown in Fig. 5.3 through 5.6 were taken with a tank circuit resonant frequency of 5 KHz, and a converter rated to deliver 2000 A at 500 KV line-to-line voltage. The uncompensated power system was set with a zero phase angle difference between busses so that no power could be delivered without the HFLC circuit in operation. The HFLC reference currents were set independently on each side so that 1500 MW was transferred in either direction, and the reactive power supplied to one system was independent from the other, in both magnitude and direction.

Fig. 5.7 through 5.10 show typical waveforms for steady-state operation of the HFLC series compensator. Fig 5.7 shows the tank voltage. The peak tank voltage approximately equals 300 KV which is very small compared to the tank voltage of the HFLC cycloconverter, 1.3 MV. The tank voltage changes the peak value at every half cycle. The peak value of the tank voltage should be confined to a specific range for the proper operation of the HFLC. Fig. 5.8 shows the converter output voltage, ΔV . It is similar to the line voltage of the HFLC cycloconverter in Fig. 5.4, but the magnitude is smaller. Fig. 5.9 shows the unfiltered line-to-neutral voltage at the converter output on the right-hand side (system 2) of the circuit. Although unfiltered, this voltage appears much more sinusoidal than in Fig. 5.4 for the HFLC cycloconverter. This is because the actual converter output voltage of the HFLC series compensator is series-connected and

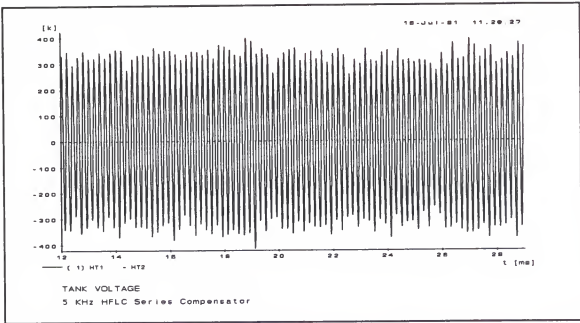


Fig. 5.7 Tank voltage of the HFLC series compensator in the simple ac power system. The required peak value of the tank voltage reference is 300 KV. The ac power system operates at the 408 KV peak line voltage and the 2828 A peak line current. The capacitance of the 5 KHz tank circuit is $1.66 \mu\text{F}$.

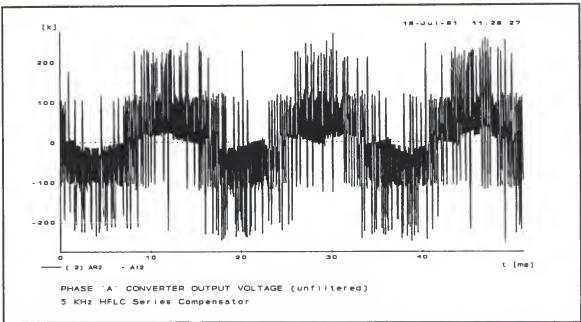


Fig. 5.8 Output voltage synthesized by the HFLC series compensator in the simple ac power system. The operating conditions are the same as those of Fig. 5.21. The total line inductance is 153 mH.

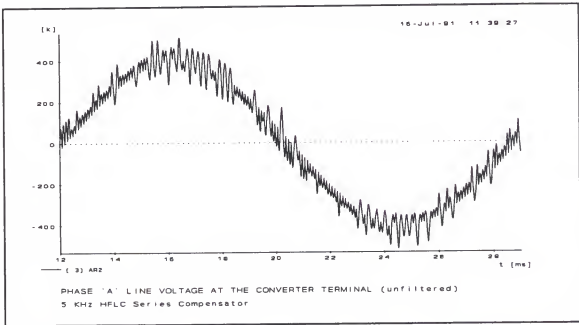


Fig. 5.9 Line voltage synthesized by the HFLC series compensator in the simple ac power system. The operating conditions are the same as those of Fig. 5.7.

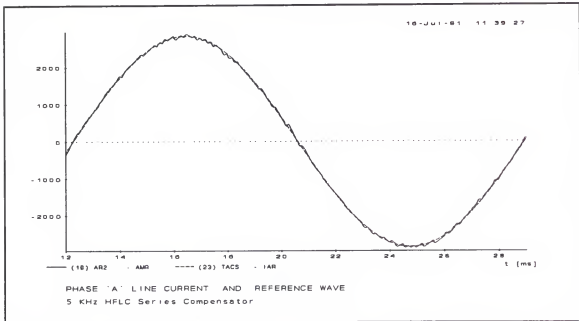


Fig. 5.10 Line current synthesized by the HFLC series compensator. The operating conditions are the same as those of Fig. 5.7

much smaller than the HFLC cycloconverter output. Therefore the line-to-neutral output contains a much smaller high frequency component from the PDM synthesis. Fig. 5.10 again shows the transmission line current I_2 flowing to system 2, plotted along with the reference current sent to the control system. The high frequency ripple is also much smaller in this case than in Fig. 5.6, due to the lower harmonic content of the converter voltage output. In this case, the actual line current is nearly equal to the ideal reference wave, so that very little if any additional filtering would be required. The results shown in Fig. 5.7 through 5.10 were taken with a tank circuit resonant frequency of 5 KHz and a converter rated to deliver 2000 A at 150 KV (series connected). The uncompensated power system was set with a 10° phase angle between the 500 KV busses, so that 750 MW is delivered to system 2. The HFLC reference currents were set to increase the power transfer to 1725 MW to system 2. In this case the HFLC control of real and reactive power flow is not completely arbitrary, since the series HFLC compensator reference current must be maintained at 90° between its series output voltage and the line current. This is because there can be no net energy flow from the converter circuit into the power system. One of the consequences of this is that reactive power cannot be independently controlled on both sides of the converter, as it can with the HFLC cycloconverter.

Fig. 5.11 through 5.14 show typical waveforms for steady-state operation of the HFLC phase shifter. Fig. 5.11. shows the converter output voltage. It is the same as Fig 5.8. Fig. 5.12 shows the unfiltered line-to-neutral voltage at the converter output on the right-hand side (system 2) of the circuit. For the same reason as the HFLC series

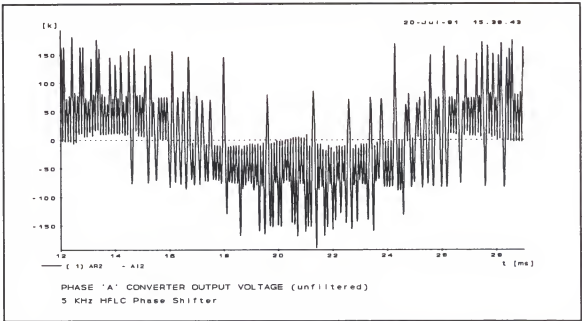


Fig. 5.11 Output voltage of the HFLC phase shifter in the simple ac power system.

The peak value of the tank voltage is 200 kV. The ac power system operates at the 408 kV peak line voltage and the 1414 A peak line current.

The capacitance of the 5 KHz tank circuit is $1.66 \mu\text{F}$.

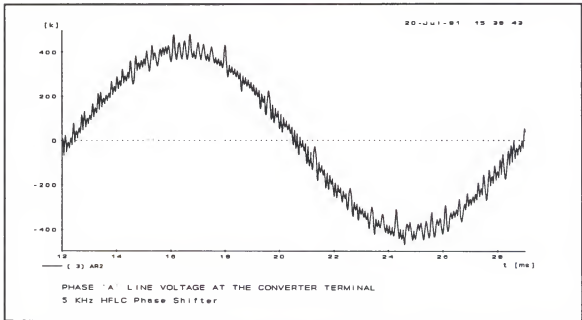


Fig. 5.12 Line voltage synthesized by the HFLC phase shifter in the simple ac power system. The operating conditions are the same as those of Fig. 5.11.

The total line inductance is 153 mH.

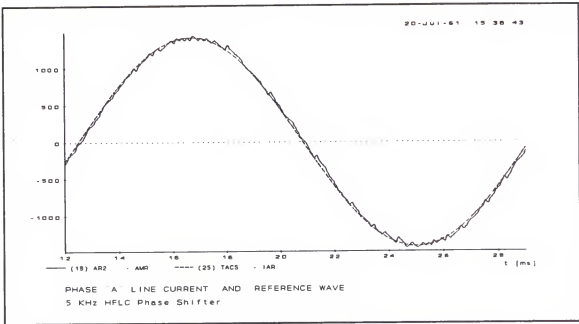


Fig. 5.13 Line current of the HFLC phase shifter in the simple ac power system. The operating conditions are the same as those of Fig. 5.11.

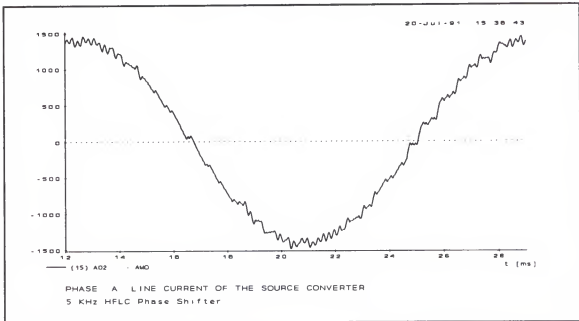


Fig. 5.14 Input line current synthesized by the HFLC phase shifter. The operating conditions are the same as those of Fig. 5.11. The input inductive filter is 50 mH. The turn ratio of the input shunt-connected transformer is 5:1.

compensator, this voltage appears much more sinusoidal than that in Fig. 5.4 for the HFLC cycloconverter. Fig. 5.13 again shows the transmission line current I_2 flowing to system 2, plotted along with the reference current sent to the control system. The high frequency ripple is also much smaller in this case than in Fig. 5.6, due to the lower harmonic content of the converter voltage output. In this case the actual line current is nearly equal to the ideal reference wave, so that very little if any additional filtering would be required. Fig. 5.14 shows the line current in the input converter which is similar to Fig. 5.6 in the case of the HFLC cycloconverter because the source converter structure is the same as the structure of the HFLC cycloconverter. However the peak value is smaller than that in Fig. 5.6 because of the step-down transformer. The results shown in Figs. 5.11 through 5.14 were again taken with a tank circuit resonant frequency of 5 KHz, and a converter rated to deliver 1000 A at 150 KV (series connected). The uncompensated power system was set with a zero phase angle difference between the 500 KV busses, so that no power is delivered to system 2 without the HFLC phase shifter in operation. The phase shifter reference current was set to increase the power transfer to 866 MW to system 2. In this case the HFLC control of real and reactive power flow is similar to the HFLC cycloconverter since the phase shifter angle between its series output voltage and the line current is arbitrary. However, the control range is smaller since the series-connected phase shifter generally operates at lower output voltages.

Fig. 5.15 and 5.16 show typical waveforms for steady-state operation of the HFLC shunt compensator. Fig 5.15 shows the unfiltered converter output voltage, ΔV .

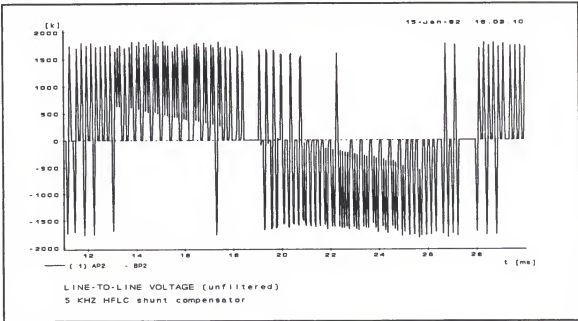


Fig. 5.15 Line-to-line voltage of the HFLC shunt compensator in the simple ac power system. The peak value of the tank voltage is 1.8 MV. The ac power system operates at the 408 KV peak line voltage and the 3793 A peak line current. The capacitance of the 5 KHz tank circuit is $0.69 \mu\text{F}$. The inductive filter was 100 mH.

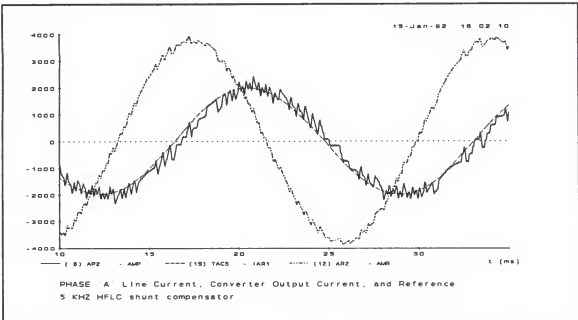


Fig. 5.16 Line current, the output current and the output current reference of the HFLC shunt compensator in the simple ac power system. The operating conditions are the same as those of Fig. 5.15. The peak value of the output current is 1964 A.

It is similar to the converter output voltage of the HFLC cycloconverter and it has the same magnitude. The peak value of tank voltage was 1.8 MV. The tank voltage of the HFLC shunt compensator should be greater than that of the HFLC cycloconverter but the number of switching devices in the HFLC shunt compensator is half that of the HFLC cycloconverter. Fig 5.16 shows the converter output current, I_c , plotted along with the reference current sent to the control system, and the transmission line current I_2 , flowing to system 2. The high frequency ripple in the line current is almost the same as that in Fig. 5.6 of the HFLC cycloconverter. Therefore, HFLC shunt compensator also requires additional inductive filtering to suppress the harmonics in the line current because of the high tank voltage. The results shown in Fig. 5.15 and 5.16 were taken with a 5 KHz and 1.8 MV tank voltage with 100 mH inductive filters. The uncompensated power system was set with 30° phase angle between the 500 KV busses, so that 2167 MW and 580 MVAR were delivered to system 2. The HFLC shunt compensator increased the power transfer to 2322 MW to system 2, and corrected the power factor of system 2 to one. In this case, the HFLC control of real and reactive power flow is not completely arbitrary; the reason is that the HFLC shunt compensator reference current must maintain 90° between its output voltage and the output current because there can be no net energy flow from the converter circuit into the power system. One of the consequences of this is that reactive power cannot be independently controlled, as it can with the HFLC cycloconverter.

5.3 Harmonic Analysis of Steady-State Output of HFLCs

Each configuration of HFLCs was evaluated for its characteristic harmonic output. This was done through Fourier analysis of typical converter waveforms produced by the EMTF simulation since analytical determination of harmonics produced by the CRWPDM control would be very difficult. This method of control attempts to minimize overall deviation from the sinusoidal reference, which produces a rather unpredictable low frequency spectrum that changes with operating conditions. Although the lower order harmonics in the output of the HFLC is normally small, harmonic output under typical operating conditions produces important data for a thorough investigation of the HFLC concept. This information will lead to efficient filtering techniques and may suggest alternate methods of control that produce lower levels of harmonics. To evaluate harmonic output, the frequency spectrum and the total harmonic distortion (THD) are used.

Fig. 5.17 and 5.18 show the frequency spectrum up to approximately 10 KHz for typical waveforms of the HFLC cycloconverter, under the same conditions as in Fig. 5.3 through 5.6. Fig. 5.17 shows the spectrum of the unfiltered line voltage, while Fig. 5.18 shows that for the transmission line current. It is clear from these graphs that the high amplitude harmonics occur mainly at the higher frequencies, well above those normally of concern in power systems. As expected, the dominant harmonics occur around the tank frequency of 5 KHz and also around twice the tank frequency (10 KHz), due to the rectification effect of the PDM controlled switching circuit. These high frequency harmonics may be easily and economically filtered. The spectrum of the line current

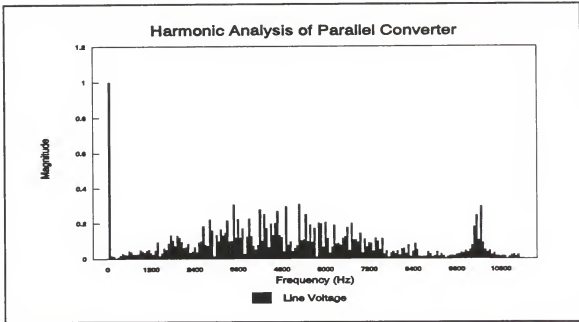


Fig. 5.17 Frequency spectrum for the line voltage synthesized by the HFLC cycloconverter in the simple ac power system. The peak tank voltage was 1.3 MV. The ac power system operates at the 408 KV peak line voltage and the 2828 A peak line current.

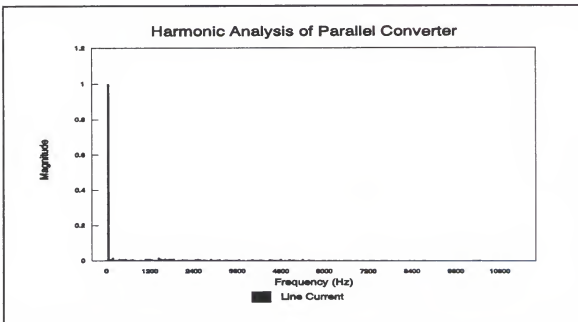


Fig. 5.18 Frequency spectrum for the line current synthesized by the HFLC cycloconverter in the simple ac power system. The operating conditions are the same as those of Fig. 5.17.

bears this out by showing that the transmission line and small added inductive filter offer substantial filtering. The effect of the inductive filtering was shown in Figs. 2.11 and 2.12 in Chap. 2. The inductive filter consumes reactive power, however, which is supplied by the HFLC cycloconverter. Fourier analysis out to the 21st harmonic of the line currents in these cases showed a total harmonic distortion (THD) of only 3% in Fig. 5.18, with an 81 mH external filter plus the 77.5 mH line impedance, and 1% in Fig. 2.12 with the 323 mH inductive filter. The higher harmonics in current can be eliminated with small inductive filters. The spectrum of the line current also suggests that system voltages away from the converter should also have relatively low levels of lower order harmonics. That is, the harmonic component in the line voltage disappears through transmission line impedance. Appendix F shows typical THD of line voltages versus the distance from the HFLC cycloconverter.

Fig. 5.19 and Fig. 5.20 show the frequency spectrum for typical waveforms of the HFLC series compensator operating under the same conditions depicted in Fig. 5.7 through 5.10. Fig. 5.19 shows the spectrum of the unfiltered line-to-neutral voltage at the converter output, while Fig. 5.20 shows that for the transmission line current. It is clear from these graphs that both the voltage and current harmonics for the series-compensated system are extremely low and occur at the frequencies well above those normally of concern in power systems. Although these high frequency harmonics may be easily and economically filtered, it is possible the system could operate satisfactorily without filters. Fourier analysis which was taken out to the 21st harmonic showed that the voltage at the converter output had a THD of less than 2% and the line current a THD

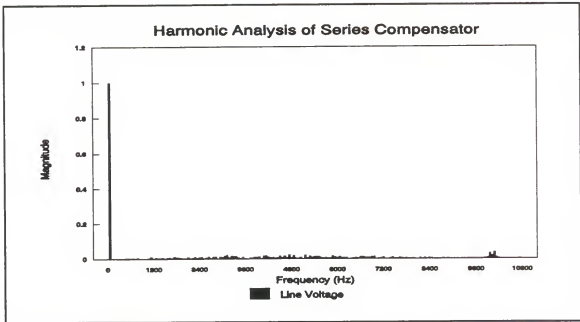


Fig. 5.19 Frequency spectrum for the line voltage synthesized by the HFLC series compensator in the simple ac power system. The peak tank voltage was 300 KV. The ac power system operates at the 408 KV peak line voltage and the 2828 A peak line current.

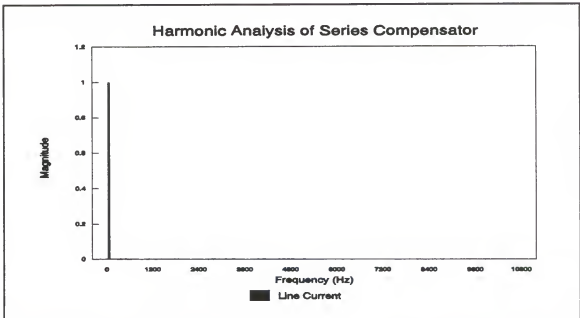


Fig. 5.20 Frequency spectrum for the line current synthesized by the HFLC series compensator in the simple ac power system. The operating conditions are the same as those of Fig. 5.19.

of well under 1%. These extremely low harmonics are substantially less than those observed in the unfiltered parallel-connected cycloconverter. This is due mainly to the relatively low tank voltage, which is series injected in the system, with a resulting low proportion of high frequency components from line to neutral.

Fig. 5.21 through 5.24 show the frequency spectrum for typical waveforms of the HFLC phase shifter, operating under the same conditions as in Fig. 5.11 through 5.14. Fig. 5.21 shows the spectrum of the unfiltered line-to-neutral voltage at the converter output, while Fig. 5.22 shows that for the transmission line current. Similar to the series compensator results, it is again clear from these graphs that both the voltage and current harmonics for the series-connected phase shifter are extremely low. Fourier analysis out to the 21st harmonic showed that the voltage at the converter output had a THD of about 1.3% and the line current a THD of about 1%. These extremely low harmonics are again substantially less than those observed in the HFLC cycloconverter. However, Fig. 5.23 and Fig. 5.24 show that the harmonic spectrums of the output voltage and the output current of the input converter of the HFLC phase shifter are the same as the spectrums of the HFLC cycloconverter because the input converter is parallel-connected to the ac power system. This is the reason for the inductive filtering requirement in the input converter side.

Fig. 5.25 and Fig. 5.26 show the frequency spectrum for typical waveforms of the HFLC shunt compensator, operating under the same conditions as in Fig. 5.15 and 5.16. Fig. 5.25 shows the spectrum of the unfiltered line-to-neutral voltage at the converter output, while Fig. 5.26 shows the spectrum for the transmission line current.

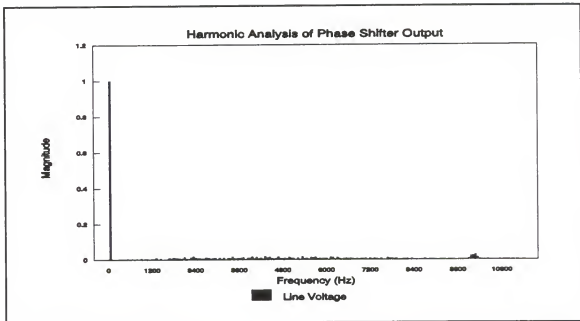


Fig. 5.21 Frequency spectrum for the line voltage synthesized by the HFLC phase shifter in the simple ac power system. The peak tank voltage was 200 KV. The ac power system operates at the 408 KV peak line voltage and the 1414 A peak line current.

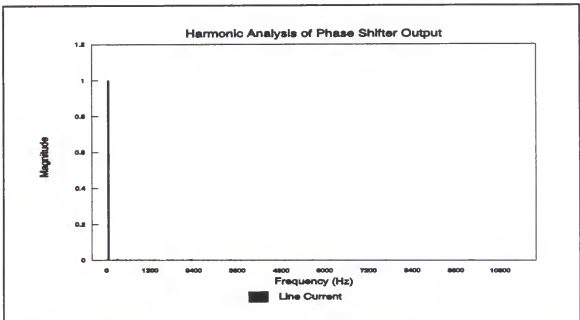


Fig. 5.22 Frequency spectrum for the line current synthesized by the HFLC phase shifter in the simple ac power system. The operating conditions are the same as those of Fig. 5.21.

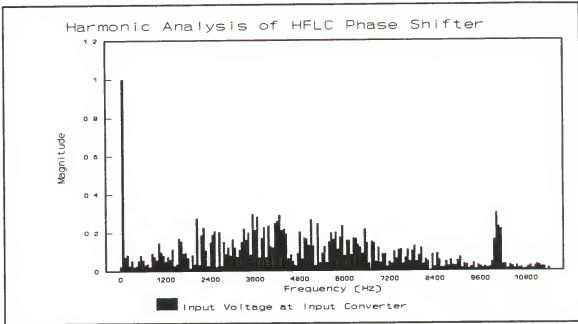


Fig. 5.23 Frequency spectrum for the input converter line voltage synthesized by the HFLC phase shifter in the simple ac power system. The peak tank voltage was 200 KV. The turn ratio of the input shunt-connected transformer is 5:1. The peak input line current is 1414 A.

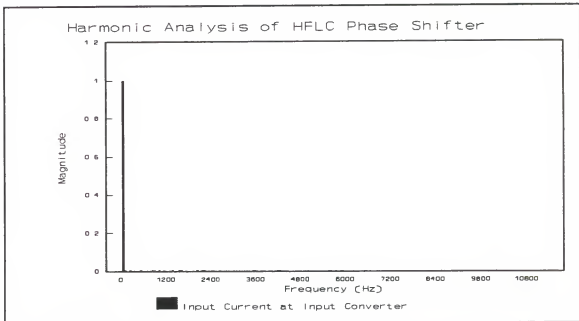


Fig. 5.24 Frequency spectrum for the input converter line current synthesized by the HFLC phase shifter. The inductive filter is 50 mH. The operating conditions are the same as those of Fig. 5.23.

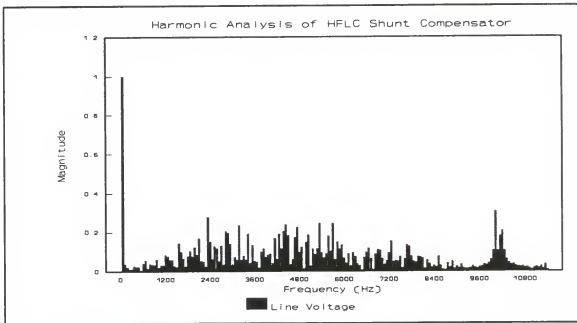


Fig. 5.25 Frequency spectrum of the line voltage synthesized by the HFLC shunt compensator. The peak tank voltage was 1.8 MV. The ac power system operates at the 408 KV peak line voltage and 3793 A peak line current. The inductive filter was 100 mH.

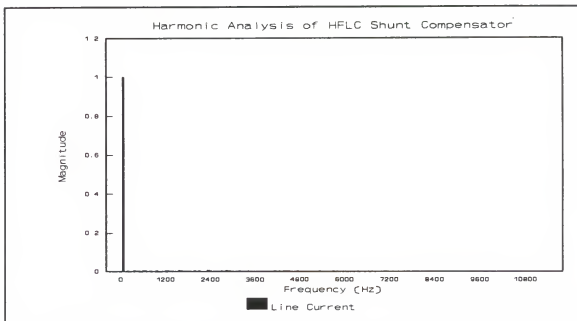


Fig. 5.26 Frequency spectrum of the line current synthesized by the HFLC shunt compensator. The operating conditions are the same as those of Fig. 5.25.

It is clear from these graphs that both the voltage and current harmonics for the HFLC shunt-compensated system are the same as those for the HFLC cycloconverter system. Therefore, the high frequency harmonics in the HFLC shunt compensator can be easily filtered with additional inductive filters, and the harmonic component in the line voltage disappears through transmission line impedance.

5.4 Transient Analysis of HFLCs in A Simple AC Power System

In order to fully evaluate the power flow control scheme and the tank voltage control scheme, transient simulations were performed in the simple ac power system model. In order to properly tune the control systems for the very complex utility test model, it is necessary to make the transient evaluation of the HFLCs in a simple ac power system. The designed characteristics of controllers can be tested by step changes in the power command setting and in the peak tank voltage command setting. Table 5.1 shows the designed characteristics of power flow controllers of HFLCs. Table 5.2 also shows the designed characteristics of tank voltage controllers of HFLCs.

Table 5.1 The designed characteristics of power flow controller of HFLC

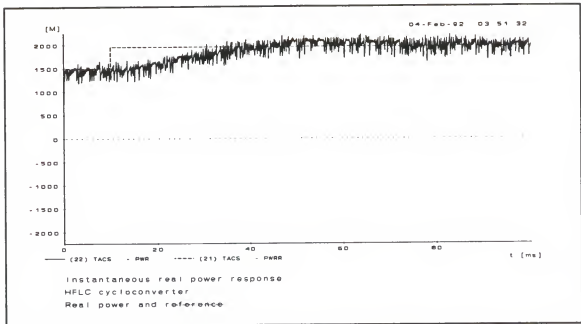
	HFLC cycloconverter	HFLC series compensator	HFLC phase shifter	HFLC shunt compensator
Damping ratio	0.6	0.6	0.6	0.6
Settling time	84 ms	84 ms	84 ms	84 ms
Frequency	80.0	80.0	80.0	80.0
Percent overshoot	10%	10%	10%	10 %
Order of controller	2	2	2	2

Table 5.2 The designed characteristics of tank voltage controller of HFLCs

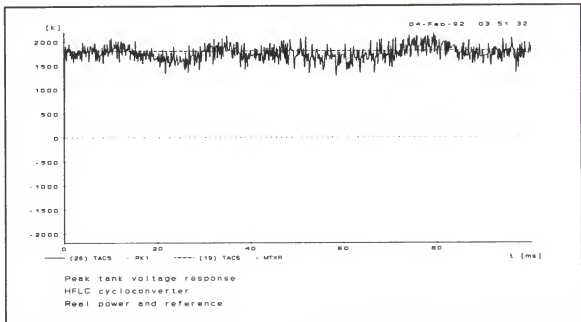
	HFLC cycloconverter	HFLC series compensator	HFLC phase shifter	HFLC shunt compensator
Damping	0.6	0.6	0.6	0.6
Settling time	16.7 ms	16.7 ms	16.7 ms	16.7 ms
Frequency	400.0	400.0	400.0	400.0
Overshoot	10%	10%	10%	10 %
Order of controller	2	2	2	2
Derivative control	Yes	Yes	Yes	Yes
Total Damping	4.0	4.0	4.0	4.0

Fig. 5.27 shows results of the HFLC cycloconverter transient performance with the simplified test model for a 30% step change in the real power reference setting. The system is initially operating with the cycloconverter forcing 1500 MW down the line with a phase angle difference of 0° between buses. As shown in Fig. 5.27, the real power changes very quickly and smoothly to its new 1950 MW level with small overshoot, and the tank voltage quickly stabilizes after a brief transient. Fig. 5.28 shows the transient response to a step change in tank voltage reference from 1.3 MV to 1.9 MV, which is also quite smooth, yet somewhat oscillatory, and results in virtually no change in the power flow. This further demonstrates the ability to continuously adjust the tank voltage to minimize operating cost, without affecting transmitted power.

Fig. 5.29 and Fig. 5.30 show results of the HFLC series compensator transient performance with the simplified test model for a 30% step change in the real power reference setting, and for a step change in the tank voltage reference from 150 KV to 250

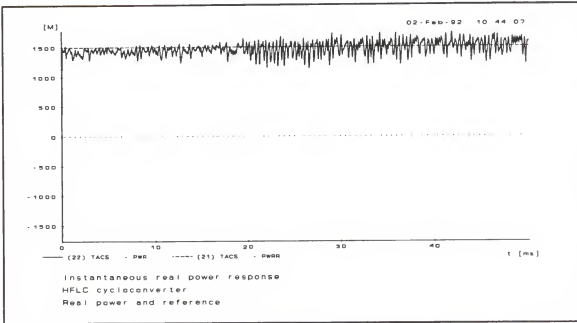


(a)

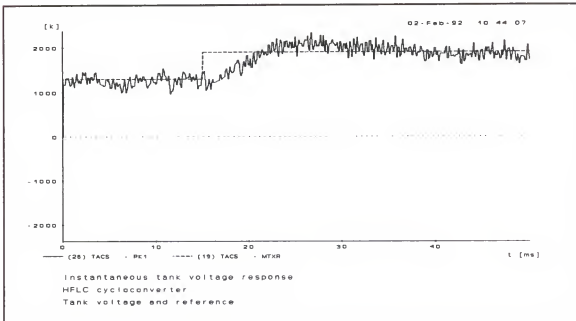


(b)

Fig. 5.27 The transient response of the HFLC cycloconverter to 30% step change of power reference; the instantaneous real power and reference (a), the tank voltage and the 1.8 MV reference (b).

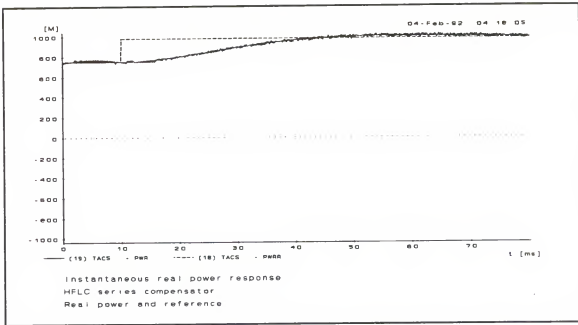


(a)

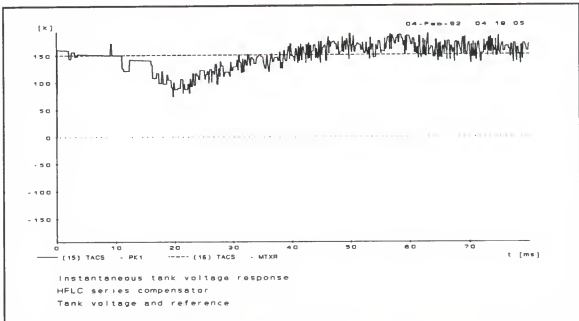


(b)

Fig. 5.28 The transient response of the HFLC cycloconverter to 600KV step change of tank voltage reference; the instantaneous real power and 1500 MW reference (a), the tank voltage and the reference (b). V_t was initially 1.3 MV.

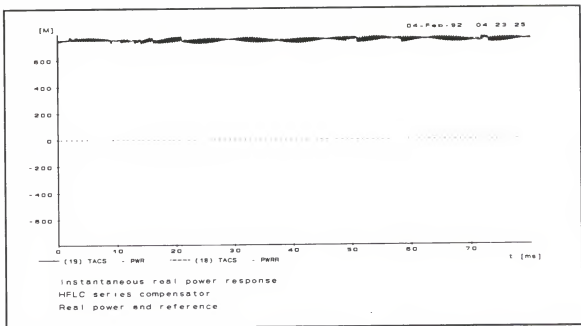


(a)

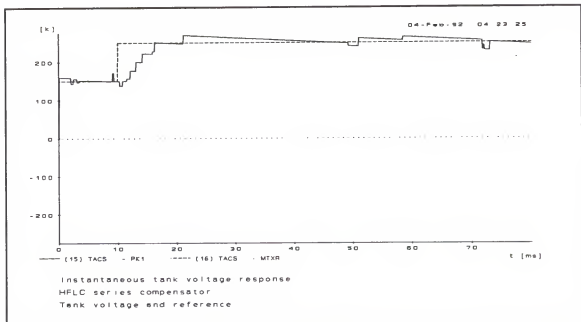


(b)

Fig. 5.29 The transient response of the HFLC series compensator to 30% step change of power reference; the instantaneous real power and reference (a), the tank voltage and the 150 kV reference (b).



(a)



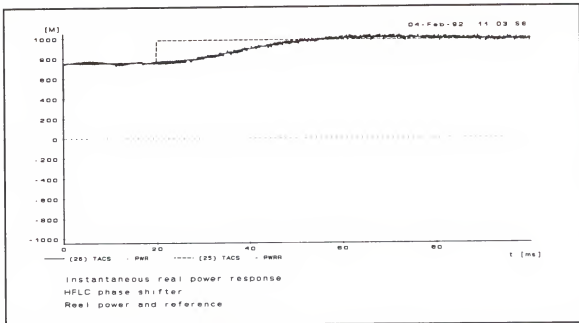
(b)

Fig. 5.30 The transient response of the HFLC series compensator to 100KV step change of tank voltage reference; the instantaneous real power and 752.6 MW reference (a), the tank voltage and the reference (b).

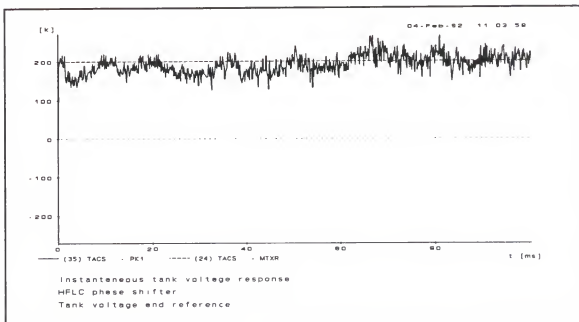
KV. The system is initially operating without compensation, transmitting 753 MW at 10° phase angle difference. As shown in Fig. 5.29, the change in real power is very smooth, with small overshoot, and the tank voltage quickly stabilizes after a brief transient undershoot. Fig. 5.30 shows the transient response to a step change in tank voltage reference from 150 KV to 250 KV, which is also quite smooth although somewhat oscillatory, and results in virtually no change in the power flow. This also demonstrates the ability to continuously adjust the tank voltage to minimize operating cost, without affecting transmitted power.

Fig. 5.31 and Fig 5.32 show results of the phase shifter transient performance with the simplified test model for a 30% step change in the real power reference setting, and for a step change in the tank voltage reference from 200 KV to 300 KV. The system is initially operating without compensation, again transmitting 735 MW at a phase angle difference of 10° . As shown in Fig. 5.31, the change in real power is very smooth, with small overshoot. Fig. 5.32 shows the transient response to the large step change in tank voltage reference. Again, the response is fast and quite smooth and results in virtually no change in the power flow. This further demonstrates the ability to continuously adjust the tank voltage to minimize operating cost, without affecting transmitted power.

Fig 5.33 shows results of the HFLC shunt compensator transient performance with the simplified test model for a 10% step change in the real power reference setting. The system is initially operating with the HFLC shunt compensator forcing 2322 MW down the line with a phase angle difference of 30° between buses. As shown in Fig. 5.33, the real power changes very quickly and smoothly to its new 2555 MW level

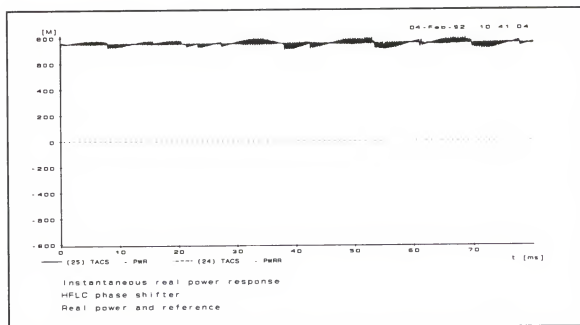


(a)

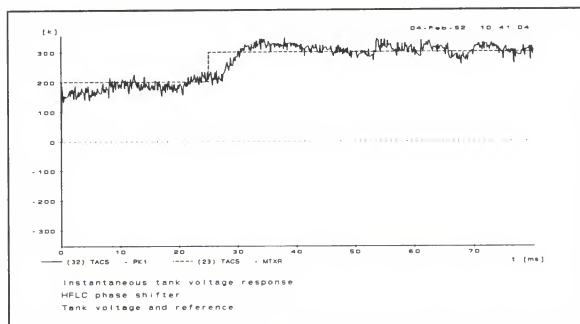


(b)

Fig. 5.31 The transient response of the HFLC phase shifter to 30% step change of power reference; the instantaneous real power and the reference (a), the tank voltage and the 200 KV reference (b).

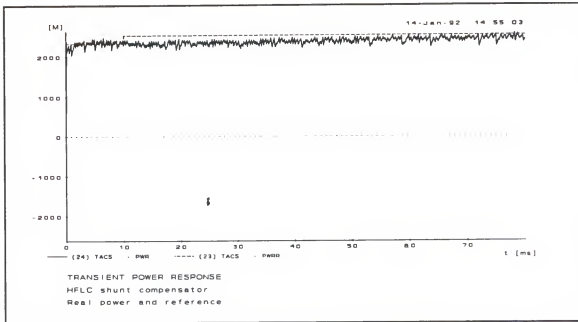


(a)

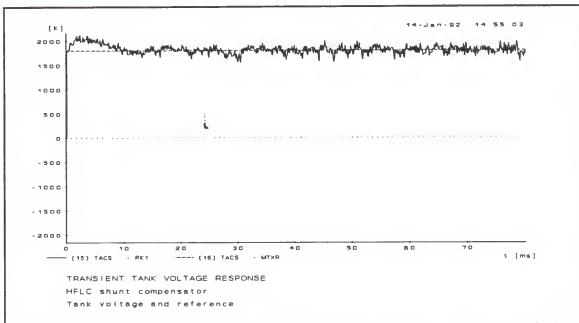


(b)

Fig. 5.32 The transient response of the HFLC phase shifter to 100 KV step change of tank voltage reference; the instantaneous real power and 752.6 MW reference (a), the tank voltage and the reference (b).

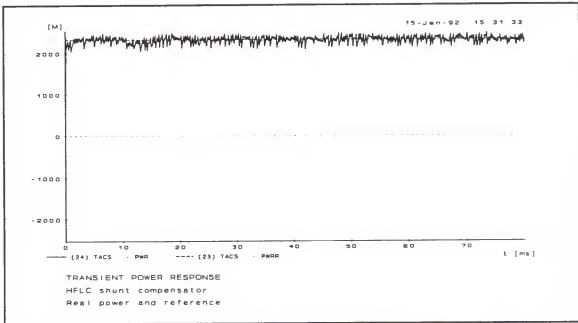


(a)

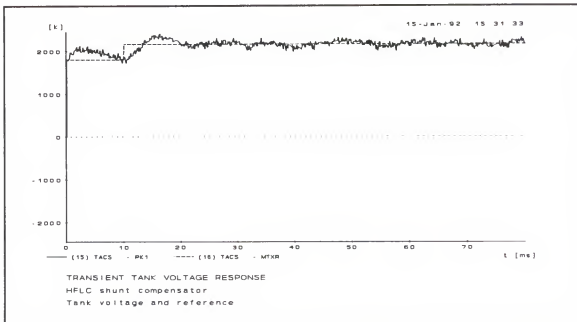


(b)

Fig. 5.33 The transient response of the HFLC shunt compensator to 230 MW (10%) step change of power reference; the instantaneous real power and reference (a), the tank voltage and the 1.8 MV reference (b).



(a)



(b)

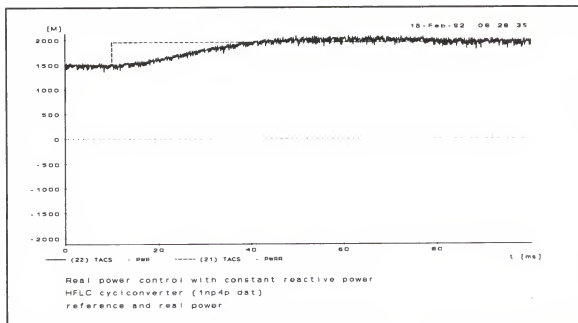
Fig. 5.34 The transient response of the HFLC shunt compensator to 360 KV step change of tank voltage reference; the instantaneous real power and the 2322.7 MW reference (a), the tank voltage and the reference (b).

with small overshoot, and the tank voltage quickly stabilizes after a brief transient undershoot. Fig. 5.34 shows the transient response to a step change in tank voltage reference from 1.8 MV to 2.16 MV, which is also quite smooth, although still somewhat oscillatory, and results in virtually no change in the power flow. This once again demonstrates the ability to continuously adjust the tank voltage to minimize operating cost, without affecting transmitted power.

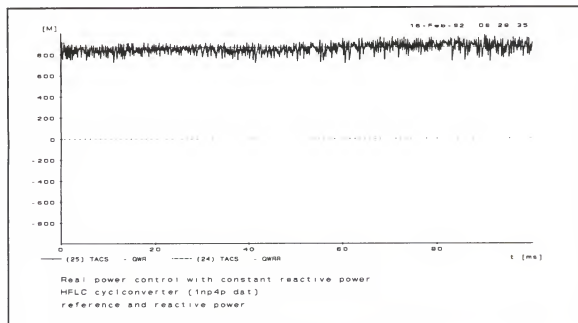
Figs. 5.27, 5.29, 5.31 and 5.33 show the tank voltage decreasing at beginning of the step change in power flow. This is because a fast transient power flow increase requires a temporary depletion of tank energy, which is proportional to the tank capacitor size and the square of the voltage. In order to minimize tank circuit costs, the size of the tank capacitor is made as small as possible, and therefore, the tank voltage becomes more sensitive to changes in tank energy flow. The response speed of the power flow control must be limited by the control system to prevent a transient collapse of the tank voltage even though HFLCs are capable of faster response.

5.5 Versatile Control Capability of HFLCs

Fig 5.35 shows that the HFLC cycloconverter can increase the real power, P_2 , continuously while keeping the reactive power, Q_2 , constant. Fig. 5.36 shows vice versa. Fig. 5.37 (a) shows that the HFLC series compensator can decrease the power transmitted below that of the uncompensated system. Fig. 5.37 (b), the phase of the line current lags the converter output voltage by 90° so the transmission line impedance is

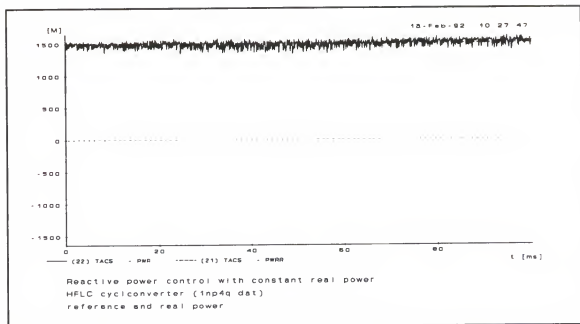


(a)

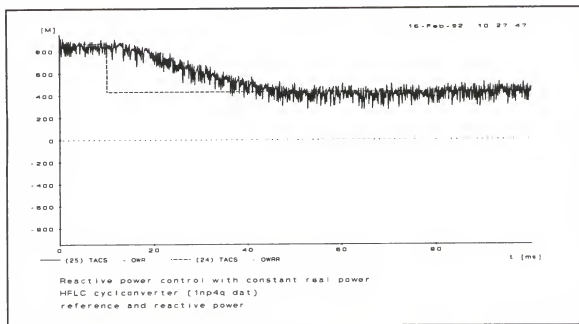


(b)

Fig. 5.35 Real power control of the HFLC cycloconverter in ac power system; real power response to 30 % step increase in real power reference (a), constant reactive power. The operating conditions are the same as those of Fig. 5.27.

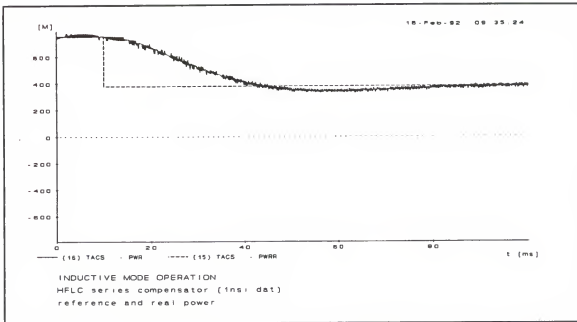


(a)

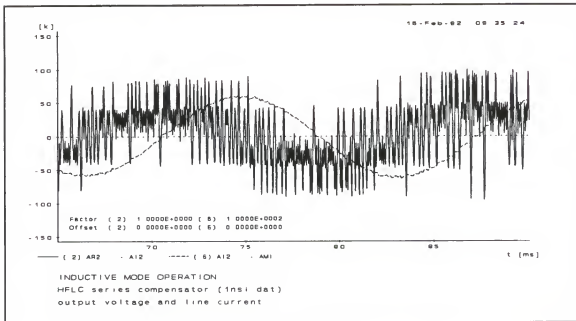


(b)

Fig. 5.36 Reactive power control of the HFLC cycloconverter in ac power system; constant real power (a), reactive power response to 50% step decrease in reactive power reference (b). Plots show the power factor correction capability of the HFLC cycloconverter.



(a)



(b)

Fig. 5.37 Real power control in inductive mode operation of HFLC series compensator; real power response to 50 % step decrease in real power reference (a), the synthesized output voltage and line current (b).

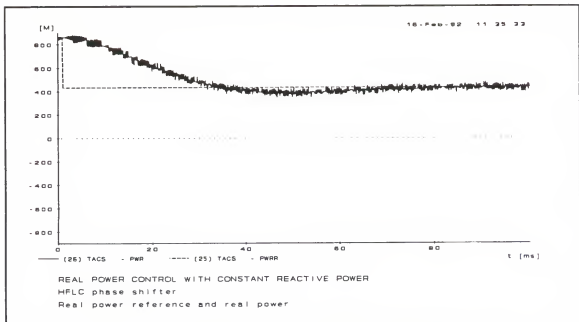
increased. From Fig. 5.37, the HFLC series compensator reduces the transmitted power continuously which also means that the transmission line impedance can be increased continuously.

Figs. 5.38 and 5.39 show the capability of the HFLC phase shifter to control the real and the reactive power independently. In Fig. 5.38, the reactive power is maintained as a constant. In Fig. 5.39, the real power is also maintained as constant.

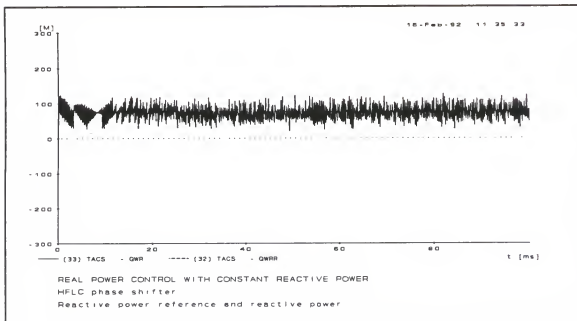
Fig. 5.40 (a) shows that the HFLC shunt compensator can decrease the power transmitted below that of the uncompensated system. In Fig. 5.40 (b), the phase of converter output current lags the converter output voltage by 90° so the HFLC shunt compensator does not absorb power from the ac power system. From Fig. 5.40, the HFLC shunt compensator reduces the transmitted power continuously; that is, the transmission line impedance can be increased continuously. In this case, the phase angle difference between the line current and line voltage at system 2 are increased.

In the ac power system, any minor disturbance can cause an unbalance between the mechanical input power and the electric output power of the generator. Because the unbalance decelerates or accelerates the generator, it may cause a stability problem in the case of an underdamped power system. HFLCs demonstrate the ability to control line impedance continuously and quickly. HFLCs can increase or decrease the transmitting power in the ac power system. The HFLCs' capability of fast line impedance control can be used to damp the power oscillation, to increase the transient stability margin, and to optimize the power flows in ac power systems.

All figures in this subsection show smooth and continuous waveforms in

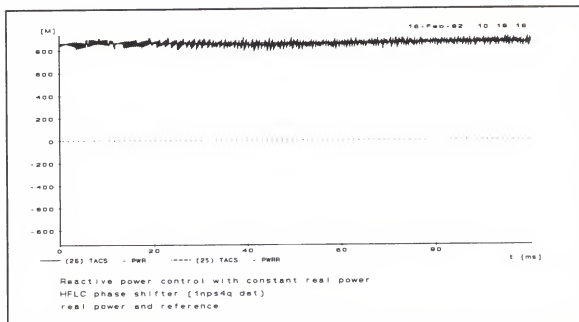


(a)

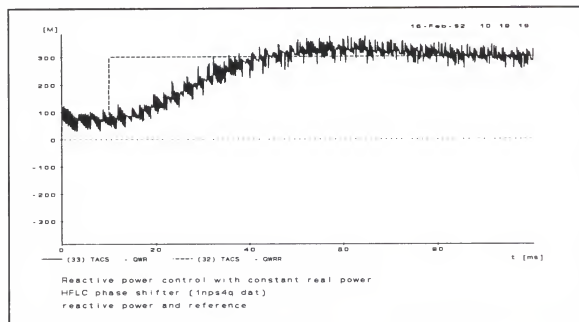


(b)

Fig. 5.38 Real power control of the HFLC phase shifter in ac power system; real power response to 50 % step decrease in real power reference (a), constant reactive power (b). Plots shows that HFLC phase shifter can provide the damping to the power oscillation of ac power system.



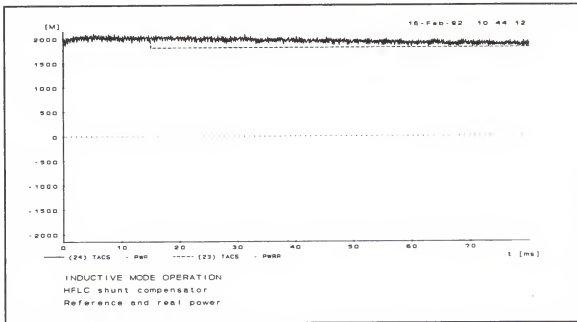
(a)



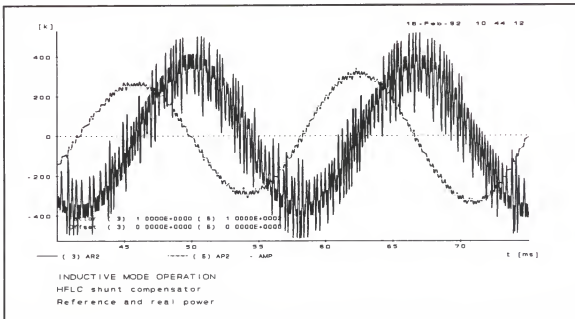
(b)

Fig. 5.39 Reactive power control of the HFLC phase shifter in ac power system; constant real power (a), 300 % step increase in reactive power reference (b).

Plot shows that the HFLC phase shifter can supply reactive power to the ac power system.



(a)



(b)

Fig. 5.40 Real power control in inductive mode operation of HFLC shunt compensator; real power response to 10 % step decrease in real power reference (a), the synthesized output voltage and output current (b).

power flow change. The smooth and continuous control of power flow by the HFLC is one advantage compared to the conventional static var compensator which shows discrete characteristics in controlling reactive power. The other advantage of HFLCs is the decoupled control capability in real power and reactive power, which are very important characteristics of the HFLC cycloconverter and the HFLC phase shifter. The real power control of the conventional HVDC converter is accompanied by a change in reactive power. If the ac system voltage is not stiff, this change in reactive power can influence the ac system voltage. Consequently, the change in ac system voltage may influence real power again, so there is fluctuation in the ac system voltage. However, the HFLC phase shifter and the HFLC cycloconverter have the smooth decoupled capability of controlling the real and reactive power.

The HFLC series compensator increases the real power flow with the lower tank voltage, but it can not improve the power factor of the ac power system. The HFLC shunt compensator can improve the power factor of the ac power system even though it does not increase/decrease the real power flow as much.

5.6 HFLCs Operation in Florida Power and Light System

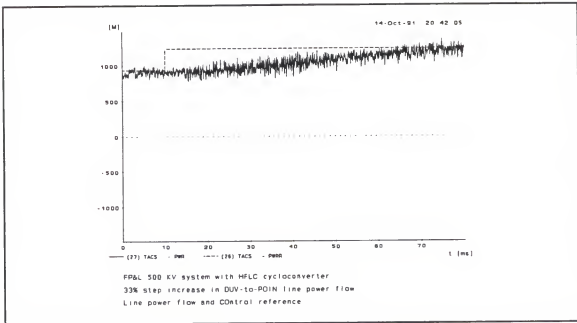
The simulation studies of HFLCs were performed in the FP&L 500 KV transmission system model shown in Fig. 5.1. The load flow data in Appendix D shows the operating condition of the FP&L system. The EMTP data for the FP&L system is given in Appendix E. Fig. 5.2 showed the EMTP model diagram and the location of HFLCs. The main concern of the FP&L system is the parallel 500 KV transmission lines

between the Duval bus in north Florida and the Poinsett bus in south Florida. Thus, in the simulation study, HFLCs were located in one of these lines near the Poinsett bus.

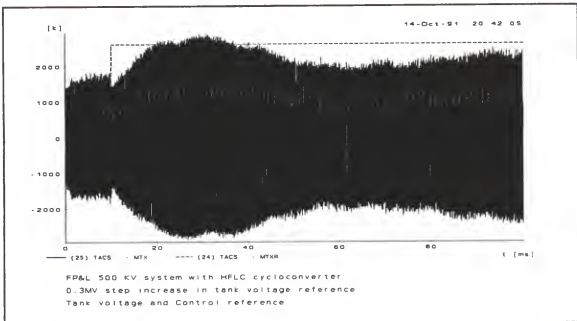
The distributed parameter model for the 500 KV transmission lines was used in the EMTP simulation studies. The line parameters were only available at 60 Hz. The EMTP simulation studies showed that high harmonic components of the HFLC output current were increased in the FP&L system. The high harmonic components come from the capacitive component of the transmission line model and the high tank voltage of the HFLC. Therefore inductive filtering is required to suppress harmonics in the output current and to isolate the tank circuit from the capacitive component of the transmission line. It is required to increase the capacitance of the tank circuit in order to reduce the effects of high harmonic components on the tank voltage.

Without the inductive filter in the FP&L system, the CRWPDM controller can not have good performance because of the high harmonic components in the line current and ripple in the tank voltage. The power flow controller and the tank voltage controller of HFLCs depend on the performance of the CRWPDM controller. Therefore, the inductive filtering is required to make the HFLCs work in the FP&L system. It is also necessary to study some better switching algorithms to synthesize the output, which can be implemented in EMTP simulation.

Fig 5.41 and Fig. 5.42 show the results of the HFLC cycloconverter transient performance in the FP&L system with a 30% step change in the real power reference setting of DUV to POIN line. The system is initially operating without compensation, transmitting 900 MW at a phase angle difference of 20° between DUV and POIN buses.

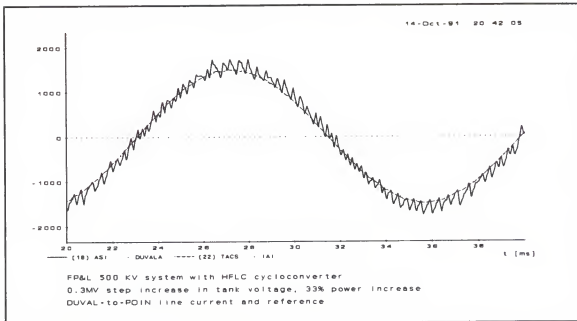


(a)

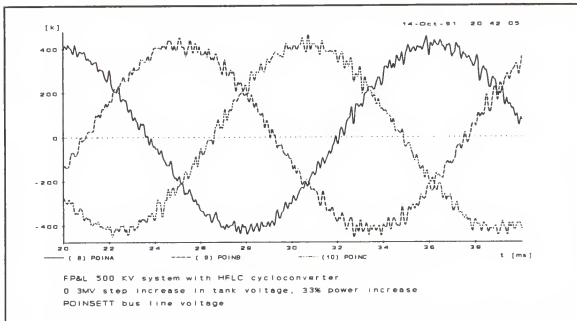


(b)

Fig. 5.41. The transient response of HFCL cycloconverter in 500 KV FP&L system to 33% step increase of real power reference with 300 KV step increase of the tank voltage; the instantaneous real power and reference (a), the tank voltage and reference (b).



(a)



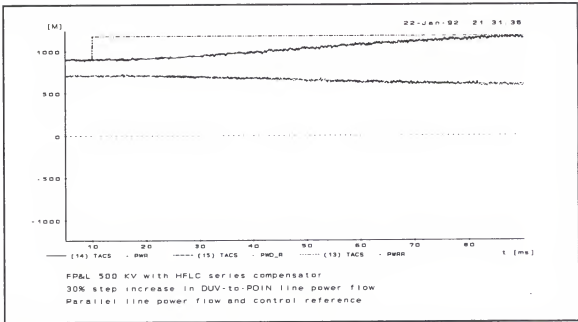
(b)

Fig. 5.42 The Line voltages at POINSETT bus and the POIN-to-DUVAL line current of FP&L 500KV system with 300 KV step change of tank voltage reference and 33% step increase of power reference; the line voltage (a), the line current (b).

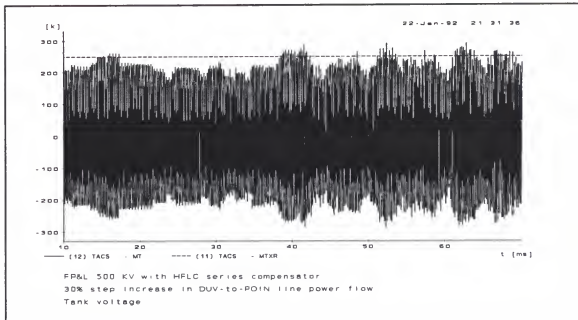
Fig. 5.41 (a) shows that the real power changes very quickly and smoothly to its new 1170 MW level, and Fig. 5.41 (b) shows that the tank voltage stabilizes after a brief transient. Fig 5.42 shows the bus voltages at Duval and at Poinsett, and it shows the line current in the Duval-Poinsett line. Even though the tank voltage of the HFLC cycloconverter is as high as 1.3 MV, Fig. 5.42 (b) shows that the harmonic components in the line current and the bus voltages were suppressed sufficiently by the added inductive filtering, 150 mH.

Fig. 5.43 (a) shows results of the HFLC series compensator transient performance in the FP&L system with a 30% step change in the real power reference setting of DUV to POIN line. The system is initially operating without compensation, transmitting 900 MW at a phase angle difference of 20° between DUV and POIN buses. Fig. 5.43 (a) shows that the change in real power is very smooth. Fig. 5.43 (b) shows the stable tank voltage during the transient. Fig 5.44 shows the bus voltages at Duval and at Poinsett and the line current in the Duval-Poinsett line. Because the tank voltage was as low as 250 KV, the harmonic components of the line current and the bus voltages were negligible without any added inductive filters.

Fig. 5.45 shows results of the HFLC phase shifter transient performance in the FP&L system with a 30% step change in the real power reference setting of DUV to POIN line. The system is in the same operating condition without compensation, again transmitting 900 MW at a phase angle difference of 20° . The peak tank voltage was 250 KV. Fig. 5.45 (a) shows that the change in real power is very smooth. Fig. 5.45 (b) shows that the harmonic components in the outputs are negligible.

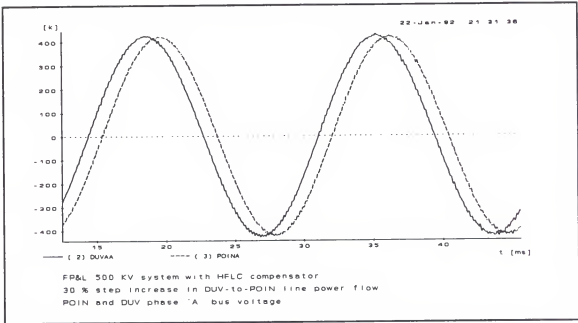


(a)

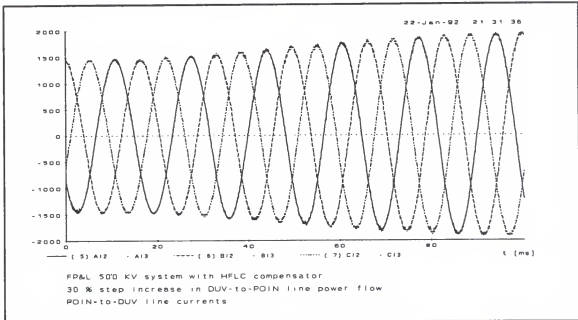


(b)

Fig. 5.43. The transient response of HFLC series compensator in 500 KV FP&L system to 30% step increase of real power reference; the instantaneous real power flows in DUV-to-POIN and DUV-to-RICE lines and reference (a), the tank voltage and reference (b).

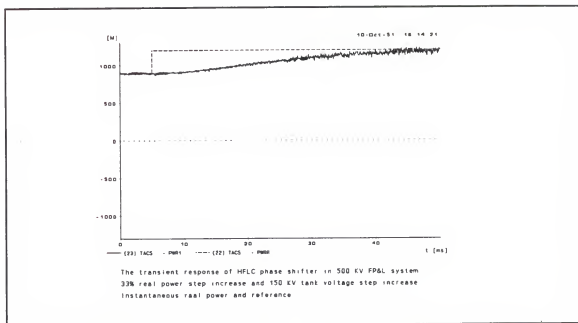


(a)

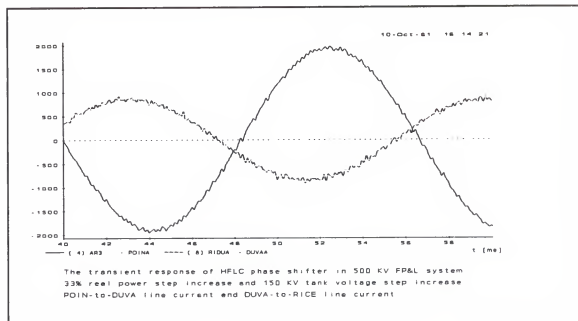


(b)

Fig. 5.44 The Line voltages at POINSETT bus and the POIN-to-DUVAL line current of FP&L 500KV system with HFCL series compensator to 30% step increase of power reference; the line voltages at POIN and DUVAL buses (a), the POIN-to-DUVAL line currents (b).



(a)



(b)

Fig. 5.45. The transient response of HFLC phase shifter in 500 KV FP&L system to 33% step increase of real power reference with 300 KV step increase of the tank voltage; the instantaneous real power and reference (a), the POISETT-to-DUVAL line current and the DUVAL-to-RICE line current (b).

Figs 5.41 (a), 5.43 (a) and 5.45 (a) show that the real power flow of the Duval-to-Rice line decreases as the real power flow of the Duval-to-Poinsett line increases. This means that the HFLCs at the Duval-to-Poinsett line in the FP&L system influences the power flows of the Duval-to-Rice line and the Rice-to-Poinsett line. Therefore, in order to accurately control the loading of the two parallel lines between the Duval bus and the Poinsett bus, a HFLC should be installed in each of the two lines. Using HFLCs as a FACTS element should control the power flow accurately and should not influence the power flow in a parallel transmission line.

5.6 HFLCs Operation during AC System Faults.

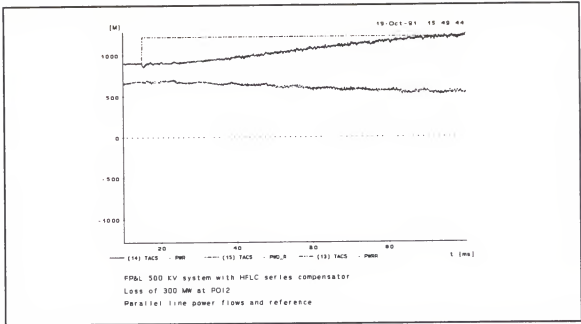
Several simulations were performed to study the HFLC operation during a fault period. The operating condition of an ac power system changes continually at a varying rate because there are always load changes, generation unit losses, transmission line trips and various types of line faults in an ac power system. The simulation studies in this section concentrate on the use of the HFLC series compensator.

Fig 5.46 (a) shows the power flows of the Duval-to-Poinsett line and the Duval-to-Rice line. When a 300 MW generation unit in the area of South Florida is lost, the power-flow controller initiates a HFLC series compensator to increase the 300 MW real power through the Duval-to-Poinsett line. Due to the existence of a closed loop between the Duval bus and the Poinsett bus, however, the HFLC series compensator also influences the parallel Duval-to-Poinsett line through the Rice bus. Fig. 5.46 (b) shows the tank voltage of the HFLC series compensator. The tank voltage has a transient period

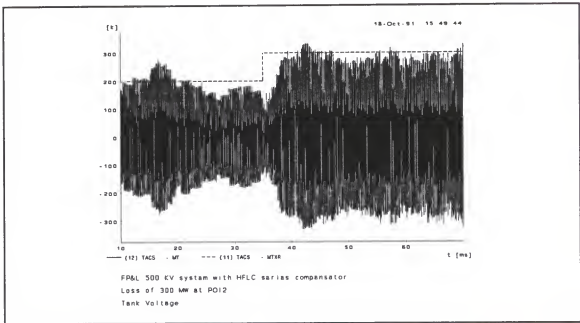
due to the unbalanced power between the Duval bus and the Poinsett bus. The tank voltage controller makes the tank voltage reach steady-state quickly and the power flow controller produces a new operating condition of the ac power system. The peak voltage reference is also shown in Fig. 5.46 (b). The initial setting of tank voltage was 200 KV, but it is not enough to increase 300 MW through DUV to POIN line, so the tank voltage was increased to 300 KV. As mentioned earlier, the tank voltage is kept at the minimum value to reduce the switching stress and loss.

Fig. 5.47 shows the transient responses to the tripping of the Duval-to-Rice transmission line. Fig. 5.47 (a) shows that total real power flow over the primary interface, initially at 900 MW, is increased to 1500 MW upon removal of the parallel lines. In other words, the power flow on the remaining line increases immediately by 600 MW. Fig. 5.47 (b) shows the line current in the remaining line. The line current magnitude is increased in order to deliver more power through the transmission line. The waveform of line current is very smooth. The transmission line impedance is still sufficient to suppress the harmonics of the line current.

Fig. 5.48 shows the result of a 3 ϕ line fault at the Duval bus without the HFLC series compensator. The 3 ϕ line fault occurs at 16.7 msec and continues to the end of the simulation. Fig 5.48 (a) and (b) shows the fault line current and the oscillatory power swing of the Duval-to-Poinsett line. The power swing did not grow in this case. However, it is possible to diverge so the ac power system suffers a stability problem. Fig. 5.49 shows that the HFLC series compensator can be used to damp out the

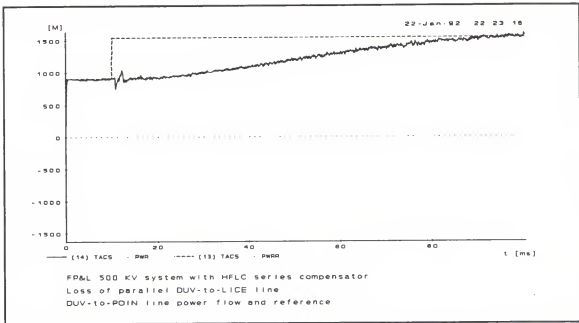


(a)

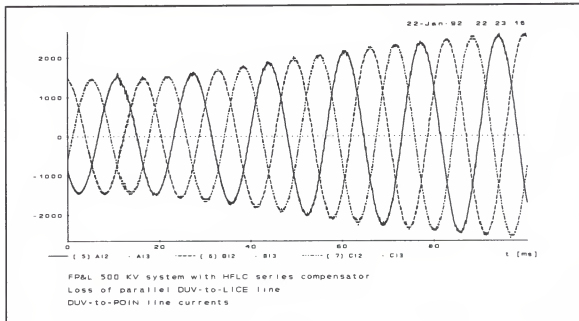


(b)

Fig. 5.46 HFLC series compensator transient response for the loss of 300 MW unit of POIN bus in FP&L 500 kV system; the instantaneous power flowing in DUV-to-POIN and DUV-to-RICE lines (a), tank voltage and reference.

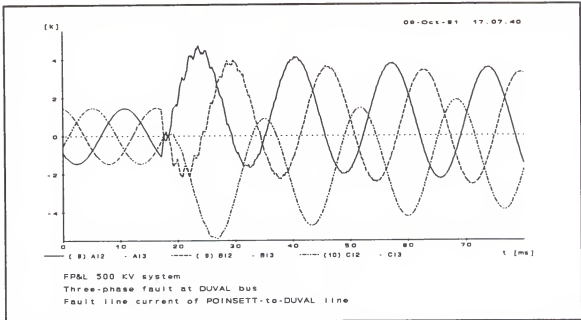


(a)

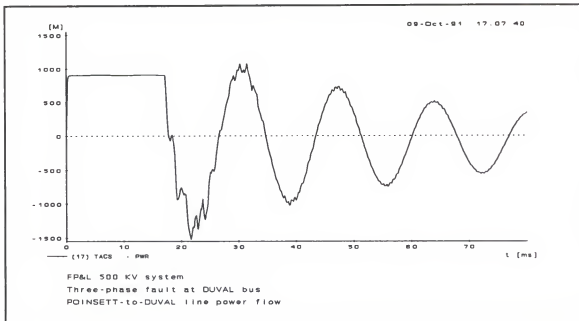


(b)

Fig. 5.47. The transient response of HFLC series compensator in 500 KV FP&L system to the loss of the parallel line which delivered 600 MW; the instantaneous real power and reference (a), the DUV-to-POIN line currents (b).

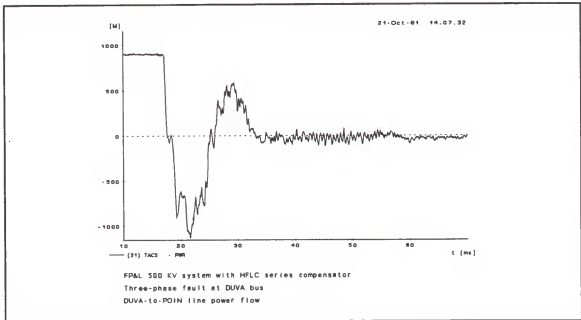


(a)

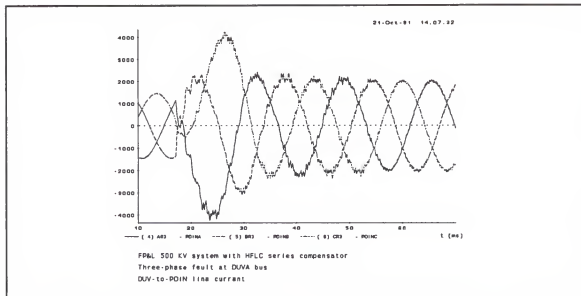


(b)

Fig. 5.48. The transient response during three-phase fault at DUVAL bus in 500 KV FP&L system without HFLCs; DUVAL-to-POINSETT line current (a), the DUVAL-to-POISETT line power flow (b).



(a)



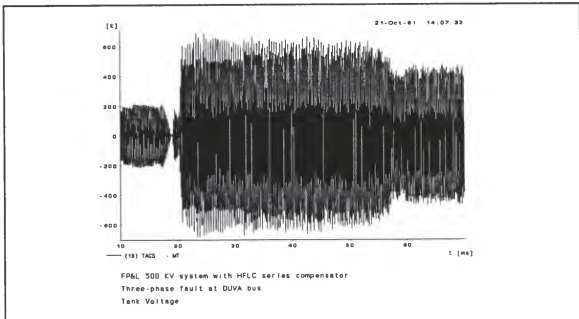
(b)

Fig. 5.49 HFLC series compensator transient response for 3ϕ fault at DUV bus in FP&L 500 KV system; instantaneous power flow of DUV-to-POIN line (a), DUV-to-POIN line fault current (b).

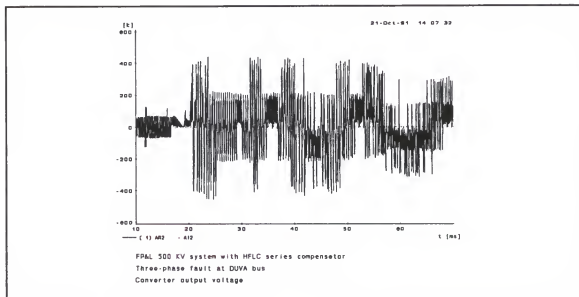
oscillatory power swing. The HFLC damps the oscillatory power swing out in a shorter period than it normally would without the HFLC.

Fig. 5.50 (a) shows the tank voltage of the HFLC series compensator. A big unbalance of power flow exists in the FP&L system after the fault occurs. It induced the overvoltage in the tank circuit because it instantaneously absorbs the unbalance of power flow. Excessive overvoltage in the tank circuit could result in the breakdown of insulation in transformer or destruction of the switching devices in the HFLC. Overvoltage should be reduced to a reasonable value. Therefore, an additional switching algorithm for the protection of the HFLC is required. Deadband control may be used for the protection of the HFLC. Therefore, when the magnitude of the tank voltage is bigger than the upper limit, the HFLC does not control output current. Instead, it tries to escape from the overvoltage. Fig. 5.50 (b) shows the converter output voltage in phase A. The high tank voltage after the fault initiates tank voltage controller action to protect the HFLC circuit. Since the HFLC does not control output current during the high tank voltage period, the converter output voltage has an arbitrary value. However after the high tank voltage is cleared, the HFLC works again to control current output.

In this section, it has been shown from the several simulations that the HFLC series compensator works continuously in various fault situations in the FP&L system. The HFLC series compensator can also be protected from overvoltages during the transient period. HFLC circuits do not suffer from the commutation failure resulting from ac system faults.



(a)



(b)

Fig. 5.50 HFLC series compensator transient response for 3ϕ fault at DUV bus in FPL&L 500KV system; tank voltage (a), converter output voltage (b).

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

This study investigated the feasibility of high frequency link converters (HFLCs) as FACTS control elements in an ac power transmission system. Four kinds of HFLCs were studied: HFLC cycloconverter, HFLC series compensator, HFLC phase shifter and HFLC shunt compensator. EMTP simulation models of the HFLCs incorporated in the ac power transmission system were developed. Each EMTP simulation model was comprised of a HFLC circuit, a control system, a measurement system and an ac power transmission system.

The evaluation of HFLCs in an ac power transmission system was performed during steady-state and transient operation by EMTP simulation and analysis. The results obtained by the simulation study of each model were compared to others. The results showed that HFLCs can be used to improve the performance of an ac power transmission system. They are able to do the following:

- 1) synthesize the required output accurately and quickly,
- 2) generate low distorted output,
- 3) control real power and/or reactive power flow of the ac power system,
- 4) increase the transmittable power of the ac power system,
- 5) increase the stability margin of the ac power system,
- 6) provide damping for power oscillations in the ac power system, and

7) protect themselves from high voltage transients.

The comparisons between HFLCs were made in the control aspect. The HFLC cycloconverter can decouple the real power control and the reactive power control with a high tank voltage which is connected to the line-to-line voltage of an ac power system. The HFLC phase shifter can also decouple the real power control and the reactive power control with a small tank voltage which is determined by the required power compensation. However, the HFLC series compensator and the HFLC shunt compensator can not decouple the real power control and the reactive power control. The HFLC series compensator can control the real power effectively with a small tank voltage without correcting the power factor of the ac power system. The HFLC shunt compensator can also control the real power flow with a high tank voltage, but is very effective in correcting the power factor of the ac power system.

The HFLC cycloconverter and the HFLC shunt compensator need inductive filters to suppress the harmonics of the line current. The input converter of the HFLC phase shifter also needs a step-down transformer and inductive filters to connect itself to the line-to-line voltage of ac power system. However, the HFLC series compensator usually increases the transmittable power without filtering. Switching components in the HFLC series compensator and the HFLC shunt compensator are half of those in the HFLC cycloconverter and the HFLC phase shifter. Therefore, the HFLC series compensator has a lower tank voltage, less switching stress, less inductive filtering and fewer switching components for the improvement of real power control capability in an ac power system. The HFLC series compensator is concluded as the most efficient application to improve

the real power transfer capability of the ac power system.

The control systems of the HFLCs were designed with the assumption that a 5 KHz current reference waveform pulse density modulation (CRWPDM) controller is accurate and fast enough to be considered as an unity transfer function system. The comparisons between the output waveforms of the HFLC power system and the waveforms of the hypothetical system proved that the assumption is proper.

More research is required so that the HFLCs can be used in the real ac power transmission system. This research should be aimed at proving that a 5-10 KHz switching device is able to operate in a utility level power system. More detailed models of switching devices are also needed, even though a small time step is required to observe the switching in an EMTP simulation. Different switching algorithms should also be considered to investigate the performance of HFLCs in practical ac transmission system. More theoretical work is also needed to design the control system of the HFLCs in order to achieve better overall performance.

APPENDIX A MEASUREMENT ALGORITHM

To measure the operating condition of an ac power system such as the magnitude of line voltage, line current, the real power and the reactive power is important because the performance of the control system depends on the accuracy of measuring. The line voltages in an ac power system are written as

$$V_a(t) = V_m \cos(\omega t + \phi) \quad (\text{A.1})$$

$$V_b(t) = V_m \cos(\omega t + \phi - 120^\circ) \quad (\text{A.2})$$

$$V_c(t) = V_m \cos(\omega t + \phi + 120^\circ) \quad (\text{A.3})$$

The line currents in ac power system are written as

$$I_a(t) = I_m \cos(\omega t + \phi - \theta) \quad (\text{A.4})$$

$$I_b(t) = I_m \cos(\omega t + \phi - \theta - 120^\circ) \quad (\text{A.5})$$

$$I_c(t) = I_m \cos(\omega t + \phi - \theta + 120^\circ) \quad (\text{A.6})$$

And the instantaneous real power flow is defined as

$$S_{3\phi}(t) = V_a(t)I_a(t) + V_b(t)I_b(t) + V_c(t)I_c(t) \quad (\text{A.7})$$

Substituting equations (A.1), (A.2), (A.3), (A.4), (A.5), and (A.6) into (A.7) transforms

equation (A.7) to

$$S_{3\phi}(t) = \frac{1}{2}V_m I_m \cos\theta(3 + O_{\cos}(t)) + \frac{1}{2}V_m I_m \sin\theta O_{\sin}(t) \quad (\text{A.8})$$

where

$$O_{\cos}(t) = \cos(2\omega t) + \cos(2\omega t - 240^\circ) + \cos(2\omega t + 240^\circ) \quad (\text{A.9})$$

$$O_{\sin}(t) = \sin(2\omega t) + \sin(2\omega t - 240^\circ) + \sin(2\omega t + 240^\circ) \quad (\text{A.10})$$

Equations (A.9) and (A.10) equal zero. The real power is defined as

$$P_{1\phi} = \frac{1}{2}V_m I_m \cos\theta \quad (\text{A.11})$$

Therefore, the real power can be measured by the instantaneous line voltage and the instantaneous line current in a symmetric 3 phase ac power system as following:

$$P_{1\phi} = \frac{1}{3}S_{3\phi}(t) \quad (\text{A.12})$$

From equations (A.1), (A.2), and (A.3), the peak value of line voltage, V_m , can be derived.

$$V_a^2(t) + V_b^2(t) + V_c^2(t) = \frac{3}{2}V_m^2 - \frac{1}{2}V_m^2 O_{\cos}(t) \quad (\text{A.13})$$

Therefore, the peak values of the line voltage and the line current are written as

$$V_m = 0.8165 \sqrt{V_a^2(t) + V_b^2(t) + V_c^2(t)} \quad (\text{A.14})$$

From the equations (A.11), (A.14) and (A.15), the phase angle difference between line

$$I_m = 0.8165 \sqrt{I_a^2(t) + I_b^2(t) + I_c^2(t)} \quad (\text{A.15})$$

voltage and line current can be calculated as

$$\theta = \cos^{-1}\left(\frac{2P_{1\phi}}{V_m I_m}\right) \quad (\text{A.16})$$

The reactive power is defined as following:

$$Q_{1\phi} = \frac{1}{2} V_m I_m \sin\theta \quad (\text{A.17})$$

Then from the equations (A.14), (A.15) and (A.16), the reactive power in equation (A.17) can be measured.

This algorithm, to provide the voltage magnitude, the current magnitude, the real power and the reactive power of the ac power system to the control system, works only for a three-phase symmetric-balanced operation. Fig. A.1 and Fig. A.2 show the phase 'A' line voltage, the line current and the peak values measured by the algorithm.

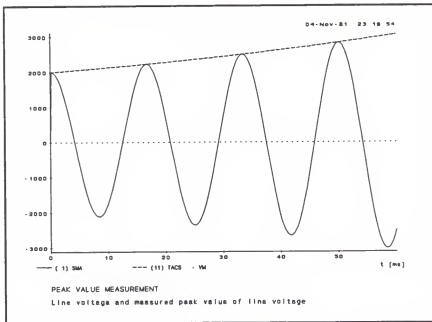


Fig. A.1 The measurement of the peak value of line voltage in symmetric 3 ϕ ac power system.

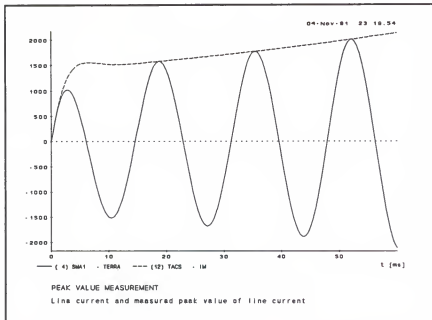


Fig. A.2 The measurement of the peak value of the line current in symmetric 3 ϕ ac power system.

APPENDIX B CIRCULATING POWER FLOW ANALYSIS

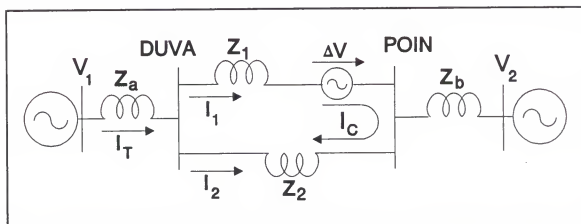


Fig. B.1 Simplified equivalent circuit of FP&L system
with a HFLC series compensator.

Fig. B.1 shows a simple equivalent circuit of the FP&L ac power transmission system. By the well-known Thevenin's circuit theorem, the northern part of FP&L system is approximated as V_1 and Z_a and the southern part of FP&L system is approximated as V_2 and Z_b . The parallel transmission lines between DUVA and POIN buses and the HFLC series compensator, ΔV , are also shown in Fig. B.1.

For the simple analysis, it is assumed that

$$Z_a = Z_b \quad (B.1)$$

$$Z_1 = Z_2 \quad (\text{B.2})$$

In the case of no compensation, the line currents, I_1 and I_T , are expressed as

$$I_1 = \frac{V_{12}}{4Z_a + Z_1} \quad (\text{B.3})$$

$$I_T = \frac{2V_{12}}{4Z_a + Z_1} \quad (\text{B.4})$$

where

$$V_{12} = V_1 - V_2 \quad (\text{B.5})$$

The HFLC series compensator on the transmission line, Z_1 , generates the closed loop current, I_c , and changes the line current, I_T , which are expressed as

$$I_c = \frac{V_{12}}{4Z_a + Z_1} + \frac{\left(\frac{4Z_a + 2Z_1}{2Z_1}\right) \Delta V}{4Z_a + Z_1} \quad (\text{B.6})$$

$$I_T = \frac{2V_{12}}{4Z_a + Z_1} + \frac{\Delta V}{4Z_a + Z_1} \quad (\text{B.7})$$

From equations (B.6) and (B.7), the line currents, I_1 and I_2 , are expressed as

$$I_1 = I_c \quad (\text{B.8})$$

$$I_2 = \frac{V_{12}}{4Z_a + Z_1} - \frac{\left(\frac{2Z_a}{Z_1}\right) \Delta V}{4Z_a + Z_1} \quad (\text{B.9})$$

From equation (B.7), (B.8) and (B.9), the power flows are expressed as

$$P_T + jQ_T = V_1 \frac{2V_{12}}{4Z_a + Z_1} + V_1 \frac{\Delta V}{4Z_a + Z_1} \quad (\text{B.10})$$

It can be expressed as

$$P_T + jQ_T = P_{T0} + jQ_{T0} + V_1 \frac{\Delta V}{4Z_a + Z_1} \quad (\text{B.11})$$

The line power flows are

$$P_1 + jQ_1 = (V_1 - I_T Z_a) * \left(\frac{V_{12}}{4Z_a + Z_1} + \frac{\left(\frac{4Z_a + 2Z_1}{2Z_1} \right) \Delta V}{4Z_a + Z_1} \right) \quad (\text{B.12})$$

$$P_2 + jQ_2 = (V_1 - I_T Z_a) * \left(\frac{V_{12}}{4Z_a + Z_1} - \frac{\left(\frac{2Z_a}{Z_1} \right) \Delta V}{4Z_a + Z_1} \right) \quad (\text{B.13})$$

HFLCs as an element of FACTS in the FP&L system should precisely control the power flow from DUVA bus to POIN bus and should not influence the power flow in the other transmission line. This simple example shows that the total power flow transmitted from DUVA bus to POIN bus is controlled by the HFLC series compensator. However, putting the HFLC in each of the two lines between DUVA bus and POIN bus is required to prevent the circulating power flow and to control the total power transmitting for DUVA bus to POIN bus.

APPENDIX C

DESIGN OF TANK VOLTAGE CONTROLLER

The tank voltage controller of High Frequency Link Converters (HFLCs) is important to synthesize the required output at the converter terminal. Unless the tank voltage is controlled properly, HFLC can not achieve the required output. However, the tank voltage control is coupled to the power flow control because the tank voltage controller generates the magnitude and the phase angle of the current reference which are able to control the power flowing to tank circuit, and the power flow controller generate the magnitude and the phase angle of the current reference which control the required power flow between the ac power systems. Therefore it is necessary to design the tank voltage controller carefully.

C.1 Unity Transfer Function System Case

The ac power system with HFLC as a controller is assumed as a unity transfer function system. Therefore the characteristics of the ac power system combined to the controller is decided by the characteristics of the tank voltage controller. The tank voltage controller is written as

$$\frac{\Delta V_t}{\Delta V_r} = \frac{G_v(s)}{1 + G_v(s)} \quad (C.1)$$

where ΔV_t is the small change of the peak tank voltage, ΔV_r is the small change of the

reference, and the transfer function, $G_v(s)$, can be arbitrarily assumed as a 2nd order transfer function as the following:

$$G_v(s) = \frac{\omega_{nt}^2}{s(s + 2\zeta_t \omega_{nt})} \quad (C.2)$$

where ζ_t is the damping factor and ω_{nt} is the undamped natural frequency. Equation (C.2) has no steady-state error to the unit-step change of the input.

The HFLC series compensator uses a single reference current as command. The changing in magnitude of current does not influence the power flow flowing to tank circuit. Therefore, the small change of the phase angle of line current can be used to control the tank voltage. Since the CRWPDM controller needs the phase angle as an input, it is necessary to convert the output of the tank voltage controller to an angle.

$$\Delta \theta = K_v \Delta V_t \quad (C.3)$$

The gain, K_v , depends on the topology of HFLCs. In HFLC series compensator,

$$P_1 = P_t + P_2 \quad (C.4)$$

where P_t equals 0 at the steady-state and

$$P_{1,2} = \frac{1}{2} V_m I_m \cos \theta_{1,2} \quad (C.5)$$

By the linearization of equation (C.4), the power flow into the tank circuit is written as

$$\Delta P_1 = P_t - \Delta P_2 \quad (C.6)$$

Equation (C.5) transforms equation (C.6) to

$$P_t = V_m I_m \sin \theta \Delta \theta \quad (\text{C.7})$$

The energy stored in tank circuit is written as

$$W_t = \frac{1}{2} C_t V_t^2 \quad (\text{C.8})$$

By the linearization of equation (C.8),

$$\Delta W = C_t V_t \Delta V_t \quad (\text{C.9})$$

$$\Delta W = 3 P_t T_t \quad (\text{C.10})$$

Where T_t is the time interval for the linearization process. Then by combining equations (C.7), (C.9) and (C.10), the small change of the phase angle of the current reference of system 2 is written as

$$\Delta \theta_2 = - \frac{C_t V_t}{3 V_{m2} I_{m2} \sin \theta_2 T_t} \Delta V_t \quad (\text{C.11})$$

The gain K_v to connect the tank voltage controller to the CRWPDM controller in HFLC series compensator is written as

$$K_v = \frac{C_t V_t}{3 V_{m2} I_{m2} \sin \theta_2 T_t} \quad (\text{C.12})$$

C.2 Linearized Model of Tank Circuit Case

By using the converter output voltage and the line current in HFLC series

compensator, the power flowing to the tank circuit is written as

$$P_t = (\Delta V) I \cos(90^\circ - \phi) \quad (\text{C.13})$$

where ϕ is a angle between the converter output voltage and the line current. To control real power to the tank circuit is achieved by controlling ϕ . In steady-state, ϕ equals to 0 with an ideal tank circuit. By the linearization of the power equation,

$$P_t = (\Delta V)(I)\Delta\phi \quad (\text{C.14})$$

The energy stored in the tank circuit is written as

$$W = \frac{1}{2}C_t V_t^2 \quad (\text{C.15})$$

By the linearization, the power flowing to the tank circuit is expressed as

$$P_t = \frac{C_t V_t}{3} \frac{dV_t}{dt} \quad (\text{C.16})$$

By substituting the equation (C.14) into (C.16),

$$\frac{dV_t}{dt} = \frac{3kI}{C_t} \Delta\phi \quad (\text{C.17})$$

where k is 0.45 for the minimum tank voltage. It is assumed that

$$\Delta\phi = K_1(V_r - V_t) \quad (\text{C.18})$$

then equation (C.17) is transformed to

differential system. The time response of equation (C.19) is written as

$$V_i(t) = (V_r - V_i(0))(1 - e^{-at}) + V_i(0) \quad (\text{C.20})$$

where

$$a = \frac{3K_1 kI}{C_r} \quad (\text{C.21})$$

The system described in equation (C.20) has no steady-state error to the unit step change of input. Therefore the choice of K_1 is the key to the design of the tank voltage controller. This case is the same as the case in which $G_v(s)$ in equation (C.1) equals K_1 .

C.3 Comparison of Various Transfer Function System of Tank Voltage Controller

$G_v(s)$ in equation (C.1) can be any type of the transfer function. To evaluate the performance of the controller, various types of the transfer functions were tested in the EMTP simulation study. The transfer functions are given in equation (C.22) through (C.26):

$$G_v(s) = \frac{\omega_{nt}^2}{s(s + 2\zeta_t \omega_{nt})} \quad (\text{C.22})$$

$$G_v(s) = \frac{1 + \alpha Ts}{1 + Ts} \frac{\omega_{nt}^2}{s(s + 2\zeta_t \omega_{nt})} \quad (\text{C.23})$$

$$G_v(s) = (1 + \alpha Ts) \frac{\omega_{nt}^2}{s(s + 2\zeta_t \omega_{nt})} \quad (C.24)$$

$$G_v(s) = K_1 \quad (C.25)$$

$$G_v(s) = K_1 + \frac{K_2}{s} \quad (C.26)$$

The tank voltage responses of the HFLC series compensator to the 100 KV step change of the tank voltage reference are given in Figs. C.1 through C.5. In Fig. C.1, ζ is 2.0 and ω_{nt} is 470.9. Fig. C.1 shows that the actual tank voltage response is not following the expected response. In Fig. C.2 and C.3, ζ is 0.6, ω_{nt} is 470.9, α is 10.0 and T is 1.44E-3. The actual tank voltage response is following the expected response. In Fig. C.4, K_1 is 0.9E-6. The tank voltage response shows a steady-state error. In Fig. C.5, K_1 is 0.9E-6 and K_2 is 15.0E-6. The steady-state error does not exist with this PI controller. The results shows that the tank voltage controller expressed as equations (C.24) and (C.26) give the best performance.

Figs. C.6 through C.8 are for the HFLC cycloconverter. In Fig. C.6, the tank voltage controller is equation (C.24). In Figs. C.7 and C.8, the tank voltage controller was expressed as equation (C.26). Figs. C.6 and C.8 show the tank voltage response to 0.6 MV step increase in voltage reference and 30% step increase in power reference. Fig. C.7 shows the tank voltage response to 0.6 MV step increase in reference.

The results of the EMTP simulation showed that the equation (C.24) gives the best tank voltage controller for the HFLCs.

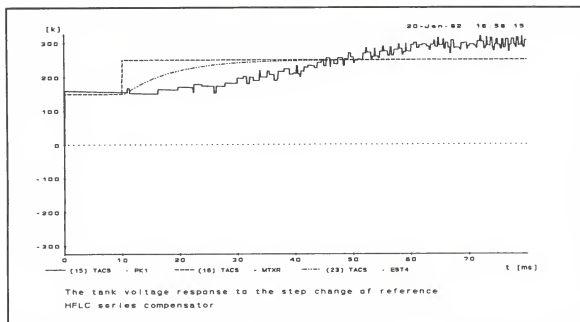


Fig. C.1. The tank voltage response to 100 kV step change in HFLC series compensator with the tank voltage controller written in equation (C.22).

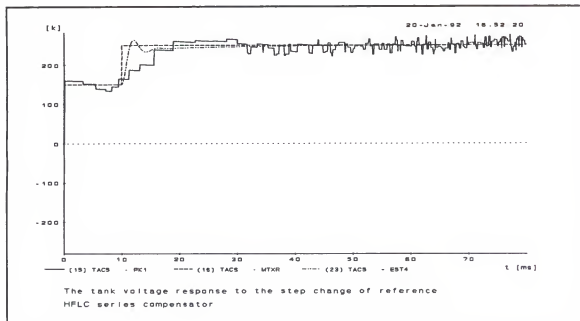


Fig. C.2. The tank voltage response to 100 kV step change in HFLC series compensator with the tank voltage controller written in equation (C.23).

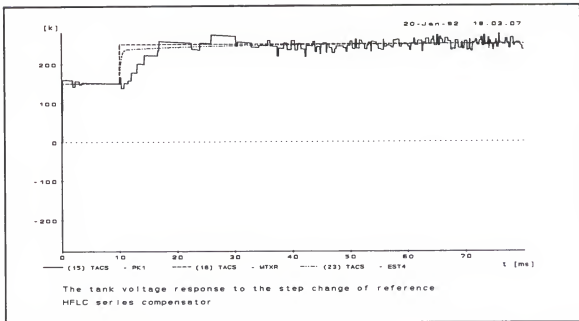


Fig. C.3. The tank voltage response to 100 kV step change in HFLC series compensator with the tank voltage controller written in equation (C.24).

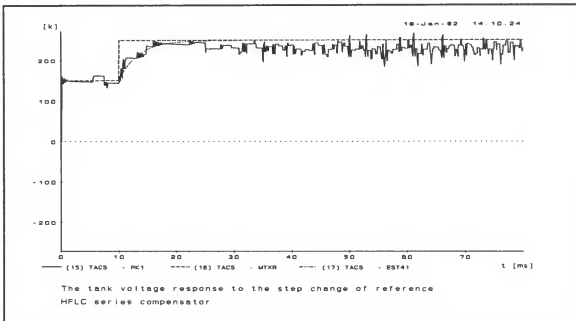


Fig. C.4. The tank voltage response to 100 kV step change in HFLC series compensator with the tank voltage controller written in equation (C.25).

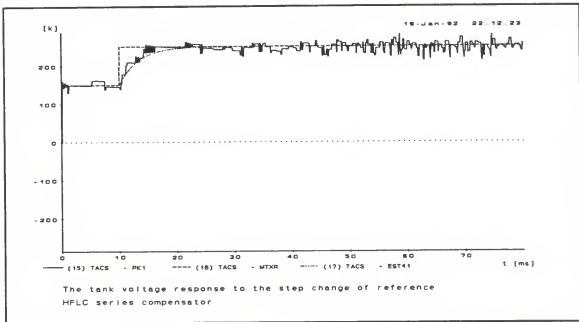


Fig. C.5. The tank voltage response to 100 kV step change in HFLC series compensator with the tank voltage controller written in equation (C.26).

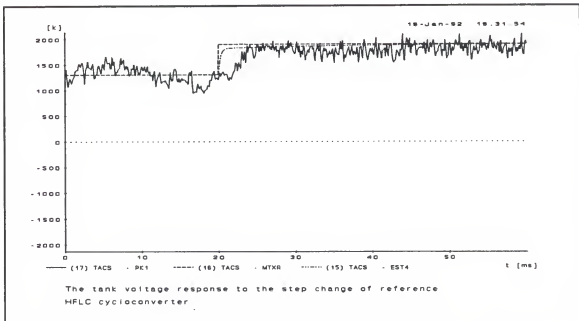


Fig. C.6. The tank voltage response to 600 kV step change in HFLC cycloconverter with the tank voltage controller written in equation (C.24).

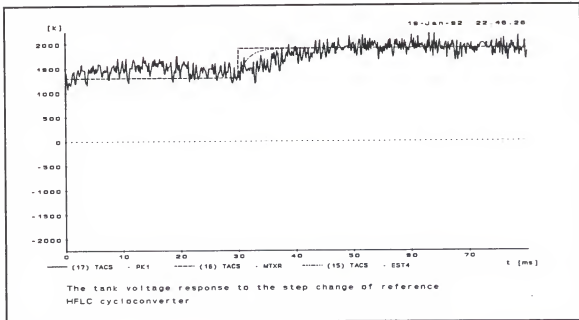


Fig. C.7. The tank voltage response to 600 KV step change in HFLC cycloconverter with the tank voltage controller written in equation (C.26).

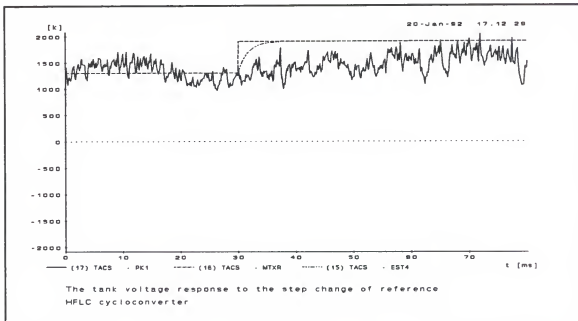


Fig. C.8. The tank voltage response to 600 KV step change in HFLC cycloconverter with the tank voltage controller written in equation (C.26).

APPENDIX D LOAD FLOW ANALYSIS FOR FPL 500 kV 13-BUS 15-BRANCH SYSTEM

BUS DATA

BUS NAME	BUS #	P load (MW)	Q load (MVAR)	Vmag (pu)	Vbas (kV)	Ty pe	P gen (MW)	Q gen (MVAR)
POIN	1	.000	.000	1.04	.00	0	.000	.000
DUVA	2	89.000	-24.900	1.04	.00	0	.000	.000
MART	3	3534.000	138.980	1.04	.00	1	1566.000	.000
MIDW	4	1456.000	.000	1.03	.00	1	1600.000	.000
RICE	5	.000	.000	1.04	.00	1	531.000	.000
DUV2	6	911.500	-73.800	1.04	.00	1	250.000	.000
NORM	7	322.000	79.500	1.03	.00	1	200.000	.000
HATC	8	.000	.000	1.04	.00	2	.000	.000
THAL	9	.000	.000	1.04	.00	0	.000	.000
WMC1	10	546.000	101.400	1.03	.00	0	.000	.000
VOGE	11	.000	.000	1.04	.00	1	1196.000	.000
POI2	12	.000	.000	1.04	.00	1	300.000	.000
SANF	13	755.300	-192.600	1.04	.00	1	200.000	.000

BUS DATA (cont)

BUS NAME	BUS #	Q genP (MVAR)	Q genW (MVAR)	P shn (MW)	Q shn (MVAR)
POIN	1	.000	.000	.000	.000
DUVA	2	.000	.000	.000	.000
MART	3	2000.000	-2000.000	.000	.000
MIDW	4	2000.000	-2000.000	.000	.000
RICE	5	2000.000	-2000.000	.000	.000
DUV2	6	2000.000	-2000.000	.000	.000
NORM	7	2000.000	-2000.000	.000	.000
HATC	8	.000	.000	.000	.000
THAL	9	.000	.000	.000	.000
WMC1	10	.000	.000	.000	.000
VOGE	11	2000.000	-2000.000	.000	.000
POI2	12	2000.000	-2000.000	.000	.000
SANF	13	2000.000	-2000.000	.000	.000

BRANCH DATA

BUS	BUS	R (pu)	X (pu)	TAP	CHARG (MVAR)	RATNG	RATNG UNITS
1	2	.0019	.0390		326.650	100.000	MVA
1	3	.0012	.0247		206.890	100.000	MVA
1	4	.0010	.0210		175.610	100.000	MVA
1	5	.0014	.0286		239.640	100.000	MVA
1	12	.0001	.0077		.000	100.000	MVA
2	5	.0005	.0104		86.970	100.000	MVA
2	6	.0000	.0037		.000	100.000	MVA
2	8	.0016	.0268		255.630	100.000	MVA
2	9	.0010	.0166		159.060	100.000	MVA
3	4	.0003	.0059		49.990	100.000	MVA
6	7	.0008	.0086		7.680	100.000	MVA
8	9	.0008	.0137		127.500	100.000	MVA
9	10	.0010	.0171		159.280	100.000	MVA

10	11	.0009	.0152	141.580	100.000 MVA
12	13	.0003	.0026	11.900	100.000 MVA

BUS VOLTAGE & POWER SUMMARY

BUS NAME	BUS #	Vmag (pu)	Vang (deg)	Pgen (MW)	Qgen (MVAR)	Plod (MW)	qlod (MVAR)
POIN	1	1.037	-63.10	.000	.000	.000	.000
DUVA	2	1.036	-42.09	.000	.000	89.000	-24.900
MART	3	1.040	-76.03	1566.000	408.040	3534.000	138.980
MIDW	4	1.031	-72.84	1600.000	-215.224	1456.000	.000
RICE	5	1.037	-45.50	531.000	6.272	.000	.000
DUV2	6	1.038	-43.64	250.000	37.077	911.500	-73.800
NORM	7	1.035	-44.19	200.000	51.205	322.000	79.500
HATC	8	1.040	-25.10	1886.357	-77.091	.000	.000
THAL	9	1.038	-30.23	.000	.000	.000	.000
WMCI	10	1.030	-24.35	.000	.000	546.000	101.400
VOGE	11	1.040	-14.63	1196.000	19.324	.000	.000
POI2	12	1.042	-64.15	300.000	-64.807	.000	.000
SANF	13	1.044	-64.92	200.000	-60.002	755.300	-192.600

POWER FLOW SUMMARY

FROM		TO		P	Q	S	%
BUS #	BUS NAME	BUS #	BUS NAME	(MW)	(MVAR)	(MVA)	RATNG
1	POIN	2	DUVA	-975.559	58.734	977.325	977.3
1	POIN	3	MART	979.851	-60.548	981.720	981.7
1	POIN	4	MIDW	864.802	-32.382	865.408	865.4
1	POIN	5	RICE	-1125.197	102.180	1129.827	*****
1	POIN	12	POI2	256.110	-67.984	264.979	265.0
2	DUVA	1	POIN	993.344	-44.464	994.339	994.3
2	DUVA	5	RICE	613.130	-72.137	617.359	617.4
2	DUVA	6	DUV2	783.903	-68.228	786.867	786.9
2	DUVA	8	HATC	-1160.839	90.529	1164.364	*****
2	DUVA	9	THAL	-1318.531	119.201	1323.909	*****
3	MART	1	POIN	-969.109	58.521	970.875	970.9
3	MART	4	MIDW	-998.887	210.541	1020.834	*****
4	MIDW	1	POIN	-857.812	-8.585	857.855	857.9
4	MIDW	3	MART	1001.811	-206.638	1022.900	*****
5	RICE	1	POIN	1142.374	-8.991	1142.409	*****
5	RICE	2	DUVA	-611.374	15.262	611.565	611.6
6	DUV2	2	DUVA	-783.615	89.590	788.719	788.7
6	DUV2	7	NORM	122.116	21.286	123.957	124.0
7	NORM	6	DUV2	-122.000	-28.295	125.238	125.2
8	HATC	2	DUVA	1181.717	-16.131	1181.828	*****
8	HATC	9	THAL	704.640	-60.960	707.272	707.3
9	THAL	2	DUVA	1335.133	-14.537	1335.212	*****
9	THAL	8	HATC	-700.967	-13.738	701.102	701.1
9	THAL	10	WMCI	-634.166	28.275	634.796	634.8
10	WMCI	9	THAL	638.021	-132.658	651.667	651.7
10	WMCI	11	VOGE	-1184.021	31.258	1184.433	*****
11	VOGE	10	WMCI	1196.000	19.324	1196.156	*****
12	POI2	1	POIN	-256.045	73.011	266.251	266.3
12	POI2	13	SANF	556.054	-137.817	572.879	572.9
13	SANF	12	POI2	-555.303	132.599	570.915	570.9

GENERATION SUMMARY

BUS NAME	BUS #	Pgen (MW)	Qgen (MVAR)	Qmin (MVAR)	Qmax (MVAR)	Vmag (pu)	Vsch (pu)
MART	3	1566.000	408.040	-2000.000	2000.000	1.04	1.04 R
MIDW	4	1600.000	-215.224	-2000.000	2000.000	1.03	1.03 R
RICE	5	531.000	6.272	-2000.000	2000.000	1.04	1.04 R
DUV2	6	250.000	37.077	-2000.000	2000.000	1.04	1.04 R
NORM	7	200.000	51.205	-2000.000	2000.000	1.03	1.03 R
HATC	8	1886.357	-77.091	.000	.000	1.04	1.04 S
VOGE	11	1196.000	19.324	-2000.000	2000.000	1.04	1.04 R
PD12	12	300.000	-64.807	-2000.000	2000.000	1.04	1.04 R
SANF	13	200.000	-60.002	-2000.000	2000.000	1.04	1.04 R

System MVA base = 100.00

Maximum # of iterations = 500 Iterations Used = 226

Mismatch Tolerance (pu) = .000100

Acceleration Factor = 1.20

of Buses 13

of Branches 15

of Unique Branches 15

	MW	MVAR		
TOTAL POWER INPUT	7729.36	104.79		
TOTAL LOAD	7613.80	28.58		
TOTAL LINE CHARGING		2093.46		
TOTAL LOSS	115.58	2169.68		
ALGEBRAIC MISMATCH	-.03	-.01		
SWING GEN (inc in tot)	1886.36	-77.09	(Bus #	8)
SHNT LD (inc in tot,+cap)	.00	.00		
MAXIMUM MW MISMATCH	.01	.00	(Bus #	12)
MAXIMUM MVAR MISMATCH	.00	.00	(Bus #	3)

APPENDIX E EMTP Input Data File for Base Case FPL 500 KV 13 Bus System

```

BEGIN NEW DATA CASE
C
C          FACTS PROJECT
C This program simulates the FPL 500 kv 3-phase system
C without the high-frequency-link converter
C (No PI section)
C
$CLOSE, UNIT=4 STATUS=DELETE
$OPEN, UNIT=4 FILE=HFLC10.PL4 FORM=UNFORMATTED STATUS=UNKNOWN
C
C DELTAT   TMAX   XOPT   COPT   EPSILN  TOLMAT  TSTART
1.70E-5  1.70E-2   60.0    0.0   1.0E-10  1.0E-20   0.0
C IOUT  IPLOT  IDOUBL  KSSOUT  MAXOUT  IPUN  MEMSAV  ICAT  NENERG  IPRSUP
100    5      1      1      1      1      0      2      0      0
C
C Beginning of 500 kv distributed parameter lines
C Line between POIN and DUVA
-1POIN-ADUVA-A      .2207 1.690 .0136 180.0
-2POIN-BDUVA-B      .0283 .5526 .0207 180.0
-3POIN-CDUVA-C
C Line between POIN and RICE
-1POIN-ARICE-A      .2207 1.690 .0136 130.0
-2POIN-BRICE-B      .0283 .5526 .0207 130.0
-3POIN-CRICE-C
C Line between RICE and DUVA
-1RICE-ADUVA-A      .2207 1.690 .0136 50.0
-2RICE-BDUVA-B      .0283 .5526 .0207 50.0
-3RICE-CDUVA-C
C Line between HATC and DUVA
-1HATC-ADUVA-A      .4844 1.954 .0127 126.0
-2HATC-BDUVA-B      .0318 .530 .0213 126.0
-3HATC-CDUVA-C
C Line between HATC and THAL
-1HATC-ATHAL-A      .4844 1.954 .0127 65.0
-2HATC-BTHAL-B      .0318 .530 .0213 65.0
-3HATC-CTHAL-C
C Line between THAL and DUVA
-1THAL-ADUVA-A      .4844 1.954 .0127 78.5
-2THAL-BDUVA-B      .0318 .530 .0213 78.5
-3THAL-CDUVA-C
C Line between WMCI and THAL
-1WMCI-ATHAL-A      .4844 1.954 .0127 73.0
-2WMCI-BTHAL-B      .0318 .530 .0213 73.0
-3WMCI-CTHAL-C
C Line between VOGI and WMCI
-1VOGI-AWMCI-A      .4844 1.954 .0127 83.0
-2VOGI-BWMCI-B      .0318 .530 .0213 83.0
-3VOGI-CWMCI-C
C Line between POIN and MART
-1POIN-AMART-A      .2625 1.815 .0133 109.0
-2POIN-BMART-B      .0368 .560 .0200 109.0
-3POIN-CMART-C
C Line between POIN and MIDW
-1POIN-AMIDW-A      .2625 1.815 .0133 93.0

```

-2POIN-BMIDW-B	.0368	.560	.0200	93.0
-3POIN-CMIDW-C				
C Line between MIDW and MART				
-1MIDW-AMART-A	.2625	1.815	.0133	26.2
-2MIDW-BMART-B	.0368	.560	.0200	26.2
-3MIDW-AMART-C				
C End of 500 kV distributed parameter lines				
C Beginning of 230 kV distributed parameter lines				
C Line between NORM and DUV2				
-1NORM-ADUV2-A	.5330	1.885	.0117	12.35
-2NORM-BDUV2-B	.0790	.720	.0157	12.35
-3NORM-CDUV2-C				
C Line between SANF and PO12				
-1SANF-APO12-A	.4900	1.982	.0021	45.20
-2SANF-BPO12-B	.0139	.142	.0028	45.20
-3SANF-CPO12-C				
C End of 230 kV distributed parameter lines				
C Beginning of source impedances using mutually-coupled R-L elements				
C Source at MART 500				
51SMAR-AMART-A	0.80	14.00		
52SMAR-BMART-B	1.05	24.92		
53SMAR-AMART-C				
C Source at MIDW 500				
51SMID-AMIDW-A	3.88	44.70		
52SMID-BMIDW-B	2.58	51.70		
53SMID-AMIDW-C				
C Source at PO12 230				
51SPO2-APO12-A	5.53	23.52		
52SPO2-BPO12-B	1.52	12.52		
53SPO2-CPO12-C				
C Source at SANF 230				
51SSAN-ASANF-A	1.27	7.45		
52SSAN-BSANF-B	1.52	6.97		
53SSAN-CSANF-C				
C Source at DUV2 230				
51SDU2-ADUV2-A	5.32	27.96		
52SDU2-BDUV2-B	2.11	15.86		
53SDU2-CDUV2-C				
C Source at NORM 230				
51SNOR-ANORM-A	1.35	9.82		
52SNOR-BNORM-B	.40	6.56		
53SNOR-CNORM-C				
C Source at RICE 500				
51SRIC-ARICE-A	4.43	32.15		
52SRIC-BRICE-B	1.18	28.28		
53SRIC-CRICE-C				
C Source at VOG 500				
51SVOG-AVOGE-A	1.08	20.83		
52SVOG-BVOGE-B	1.83	28.20		
53SVOG-CVOGE-C				
C Source at HATC 500				
51SHAT-AHATC-A	0.65	14.38		
52SHAT-BHATC-B	0.80	20.00		
53SHAT-CHATC-C				
C End of source impedances using mutually-coupled R-L elements				
C Beginning of loads using uncoupled series R-L branch				
C Load at SANF 230				
SANF-A	71.68	0.	145.1	
SANF-B				
SANF-C				
C Load at MART 500				
MART-A	76.5	3.	0.	
MART-B				
MART-C				
C Load at MIDW 500				
MIDW-A	182.5	0.	0.	
MIDW-B				
MIDW-C				
C Load at DUVA 500				

DUVA-A	2790.	0.	3.397
DUVA-B			
DUVA-C			
C Load at DUV2 230			
DUV2-A	61.89	0.	527.8
DUV2-B			
DUV2-C			
C Load at NORM 230			
NORM-A	165.6	40.89	0.
NORM-B			
NORM-C			
C Load at WMC1 500			
WMC1-A	469.5	87.2	0.
WMC1-B			
WMC1-C			
C End of loads using uncoupled series R-L branches			
C Beginning of transformers			
C Transformer at DUVA			
C Two 3-phase transformers in parallel			
TRANSFORMER THREE PHASE DUVTR .54E-2			
TRANSFORMER	1.3060	1137.T1	5.7E5
C CURRENT	FLUX		
1.3060	1137.02		
3.8490	1250.73		
10.2970	1364.43		
29.3333	1478.13		
3021.1400	2774.05		
9999			
1DUVA-A	.0600	13.54	303.0
2DUV2-A	.0125	.080	139.4
3DUVT-ADUVT-B	.0027	.1650	19.9
TRANSFORMER T1		T2	
1DUVA-B			
2DUV2-B			
3DUVT-BDUVT-C			
TRANSFORMER T1		T3	
1DUVA-C			
2DUV2-C			
3DUVT-CDUVT-A			
DUVT-A	1.0E+9		
C Transformer at POIN			
C One 3-phase transformer			
C POIN transformer 525/241.5/34.5 Y-Y-DELTA			
TRANSFORMER THREE PHASE POITR .54E-2			
TRANSFORMER	1.3060	1137.T4	5.7E5
C CURRENT	FLUX		
1.3060	1137.02		
3.8490	1250.73		
10.2970	1364.43		
29.3333	1478.13		
3021.1400	2774.05		
9999			
1POIN-A	.1198	27.08	303.0
2POI2-A	.0249	0.08	139.4
3POIT-APOIT-B	.0055	.3290	19.9
TRANSFORMER T4		T5	
1POIN-B			
2POI2-B			
3POIT-BPOIT-C			
TRANSFORMER T4		T6	
1POIN-C			
2POI2-C			
3POIT-CPOIT-A			
POIT-A	1.0E+9		
C End of transformers			
BLANK END OF BRANCHES			
BLANK END OF SWITCHES			
C Beginning of sources			
C Source at MART 500			

14SMAR-A	447440.1	60.0	-68.24	-1.0	5.0
14SMAR-B	447440.1	60.0	-188.24	-1.0	5.0
14SMAR-C	447440.1	60.0	51.76	-1.0	5.0
C Source at MIDW 500					
14SMID-A	430701.9	60.0	-55.00	-1.0	5.0
14SMID-B	430701.9	60.0	-175.00	-1.0	5.0
14SMID-C	430701.9	60.0	65.00	-1.0	5.0
C Source at PO12 230					
14SP02-A	194930.4	60.0	-60.29	-1.0	5.0
14SP02-B	194930.4	60.0	-180.29	-1.0	5.0
14SP02-C	194930.4	60.0	59.71	-1.0	5.0
C Source at SANF 230					
14SSAN-A	195681.6	60.0	-63.44	-1.0	5.0
14SSAN-B	195681.6	60.0	-183.44	-1.0	5.0
14SSAN-C	195681.6	60.0	56.56	-1.0	5.0
C Source at DUV2 230					
14SDU2-A	199249.7	60.0	-39.81	-1.0	5.0
14SDU2-B	199249.7	60.0	-159.81	-1.0	5.0
14SDU2-C	199249.7	60.0	80.19	-1.0	5.0
C Source at NORM 230					
14SNOR-A	195869.4	60.0	-42.89	-1.0	5.0
14SNOR-B	195869.4	60.0	-162.89	-1.0	5.0
14SNOR-C	195869.4	60.0	77.11	-1.0	5.0
C Source at RICE 500					
14SRIC-A	425394.7	60.0	-42.32	-1.0	5.0
14SRIC-B	425394.7	60.0	-162.32	-1.0	5.0
14SRIC-C	425394.7	60.0	77.68	-1.0	5.0
C Source at HATC 500					
14SHAT-A	428660.7	60.0	-17.14	-1.0	5.0
14SHAT-B	428660.7	60.0	-137.14	-1.0	5.0
14SHAT-C	428660.7	60.0	102.86	-1.0	5.0
C Source at VOG 500					
14SVOG-A	431926.7	60.0	-7.598	-1.0	5.0
14SVOG-B	431926.7	60.0	-127.598	-1.0	5.0
14SVOG-C	431926.7	60.0	112.402	-1.0	5.0
C End of sources					
BLANK END OF SOURCES					
POIN-APOIN-BPOIN-C					
BLANK END OF INITIAL CONDITIONS					
BLANK END OF PLOT NODES					
BLANK END OF PLOTS					
BLANK END OF SIMULATION					

EMTP Output Data File for FPL Base Case 500 kV 13 Bus System (Load Flow Only)

Sinusoidal steady-state phasor solution, branch by branch. All flows are away from a bus, and the real part, magnitude, or "pu" is printed above the imaginary part, the angle, or "deg". The first solution frequency = 6.00000000E+01 Hertz.

Bus K	Bus M	Phasor node Rectangular	Phasor node Polar	Phasor branch Rectangular	Phasor branch current	Polar	Power flow P and Q	Power loss P and Q
POIN-A		195640.41246027	423851.31153571	-760.1369065608	1533.8471301526		-.32481786603E9	-.610502661805E7
	DUVA-A	-375998.3554524	-62.5110244	1332.2458113883	119.7077001		-.125845533735E8	-.7184789.1574656
		316577.16636286	423910.55695463	1228.0012469548	1564.0699285		-.33022892651E9	
		-281920.304404	-41.6859059	-968.6731502856	-38.2671177		-.19769342531E8	
POIN-A		195640.41246027	423851.31153571	-922.2164423029	1751.573913459		-.37016787117E9	-.571898001769E7
	RICE-A	-375998.3554524	-62.5110244	1489.366652562	121.7697691		-.277082771383E8	20755555.0086773
		298234.11346367	424365.67939067	1268.29572286024	1771.8263547956		-.375866851183E9	
		-301898.3991532	-45.3498319	-1237.252840602	-44.2901614		-.69527221296E7	
RICE-A		298234.11346367	424365.67939067	-697.4083138588	977.30881720055		-.207343786662E9	682049.45125221
	DUVA-A	-301898.3991532	-45.3498319	684.65624070668	135.5286434		-.317930326778E7	21826828.6181207
		316577.16636286	423910.55695463	811.41792981229	988.52645428999		-.208025836074E9	
		-281920.304404	-41.6859059	-564.6109226806	-34.8314490		-.25006131866E8	
HATC-A		385081.86197388	425159.90990629	1687.9541383093	1845.9185606519		-.392318956724E9	-.67590172338E7
	DUVA-A	-180202.4100012	-25.0776531	-747.1453402944	-23.8757946		-.82306424446E7	21787471.9818201
		316577.16636286	423910.55695463	-1452.666362095	1824.567523935		-.38555993949E9	
		-281920.304404	-41.6859059	1103.9959645919	142.7659278		-.300181144264E8	
HATC-A		385081.86197388	425159.90990629	1050.3902490769	1113.7738848566		-.23561373607E9	-.126739193092E7
	THAL-A	-180202.4100012	-25.0776531	-370.3681833428	-19.4226785		-.23330392334E8	26079972.5588775
		366844.19940914	424547.20622133	-947.4130966709	1104.0584911647		-.234364634414E9	
		-213695.2588857	-30.2217926	566.8805660537	149.1059882		-.27495802249E7	
THAL-A		366844.19940914	424547.20622133	1780.8184106326	2040.1211158897		-.43299537094E9	-.516521029991E7
	DUVA-A	-213695.2588857	-30.2217926	-995.3793025028	-29.2027833		-.77016639767E7	29527992.3989858
		316577.16636286	423910.55695463	-1624.228445389	2026.1206310239		-.42783016064E9	
		-281920.304404	-41.6859059	1211.2170609138	143.2874280		-.372296563757E8	

Bus K	Bus M	Phasor node voltage		Phasor branch current		Power flow		Power loss	
		Rectangular	Polar	Rectangular	Polar	p and q	p and q	p and q	p and q
WNCI - A	THAL - A	381271.48821561	421578.84105256	949.01814618221	971.72431843042	-199700.689263E9	-10516624.6231E7		
		-179890.9989329	-25.2588124	-208.8365610853	-12.4104458	-43548197942E8	35096953.7400455		
		366844.19940914	424547.25682133	-833.4053139617	937.11023069754	-1986490268E9			
		-213695.2588857	-30.2217926	428.4987364491	152.7898536	104512442016E8			
VOGE - A	WNCI - A	411938.68828588	425338.58408656	1760.7653253694	1819.8751332812	-387028627745E9	-436468994384E7		
		-105921.802317	-14.4200831	-460.0553905252	-14.6429498	-150559034349E7	13072149.1445532		
		381271.48821561	421578.84105256	-1665.228904891	1816.2131895334	-3826637578E9			
		-179890.9989329	-25.2588124	725.01244413592	156.4725072	115665588011E8			
POIN - A	MART - A	195640.41246027	423851.31153571	831.69701357462	1611.9970584722	-340960058185E9	-51353104545E7		
		-375998.3554524	-62.5110244	-1380.874575816	-58.9395365	-21280918885E8	4299624.1477605		
		104505.61780328	424269.2886352	-506.8121543185	1587.6595926519	-33582474774E9			
		-411197.0392969	-75.7401998	1504.5944378386	108.6157398	255805430329E8			
POIN - A	MIDW - A	195640.41246027	423851.31153571	708.97936913156	1421.5818664395	-300999481486E9	-343681645004E7		
		-375998.3554524	-62.5110244	-1232.17014131	-60.0842732	-12756401088E8	10322604.9344093		
		126350.66309265	420874.93228093	-435.5340370108	1414.0667223577	-29756266504E9			
		-401461.3537547	-72.5298119	1345.323306081	107.9388058	243379615363E7			
MIDW - A	MART - A	126350.66309265	420874.93228093	798.09547717849	1635.2959168898	-33692643157E9	-127569810437E7		
		-101461.3537547	-72.5298119	-1427.317885092	-60.7879352	-70030944734E8	1776251.0548519		
		104505.61780328	424269.2886352	-717.8079123751	1618.0563926057	-33565073347E9			
		-411197.0392969	-75.7401998	1450.1255432142	116.3353071	718072157889E8			
NORM - A	DUV2 - A	138639.83447113	194369.17021086	-108.8278825071	280.21424885486	-25132341663E8	37583.961228946		
		-136229.1107887	-44.4975032	258.21796461579	112.8533525	-10486885104E8	-1046648.8547972		
		141001.61863725	195530.04466358	118.75845174415	274.96566150921	-251699256242E8			
		-135464.1720449	-43.8525528	-247.9970668144	-64.4116197	944023624963E7			
SAMI - A	PO12 - A	796402.743236744	196196.13994263	-818.2984031143	1395.2563034805	-13389528847E9	612339.99875323		
		-179321.8575364	-66.0430926	1130.1008255206	125.9080444	-283898319178E8	5341470.6292266		
		87360.376975786	195371.01380924	826.7540081751	1397.0163146219	-134507628464E9			
		-174751.2448353	-63.4389478	-1128.117683675	-53.7155443	-23048361295E8			
SHAR - A		165874.78792128	447440.1	-71.096732241	2466.6677478163	-506411867498E9	-319433613355E7		
		-415557.6949355	-68.2400000	-2465.642924834	-91.6516642	219266395707E9	75812244.2353411		

MART-A	104505, 61780328 -411197, 0392969	424269, 2886352 -75, 7401998	71, 096732240999 2465, 6429248336	2466, 6677478163 88, 3483358	-50321753136E9 -14345415147E9
SMID-A	247040, 46093162 -352810, 3418442 126350, 64309265 -404016, 3537547	430701, 9 -55, 0000000 420874, 93228093 -72, 5298119	1054, 8938406754 -2281, 782818763 -1054, 893840675 2281, 7828187627	2513, 828523805 -65, 1883688 2513, 828523805 114, 8116312	532819018491E9 -815194066275E7 -52567611367E8 -924664707783E9 675971685805E8
SPO2-A	96609, 507333987 -169305, 8296009 873640, 376975786 -174751, 2448353	194930, 4 -60, 2900000 195371, 01380924 -63, 4389478	517, 0053016192 -675, 9810143562 -517, 0053016192 675, 98101435619	851, 02574207387 -52, 5904375 851, 02574207387 127, 4095625	821975769543E8 550426, 05839104 4533772, 53338992 -81647150896E8 156466819009E8
SSAN-A	87496, 041603398 -175030, 6581208 79602, 743236744 -179321, 8575564	195681, 6 -63, 4400000 196196, 13994243 -66, 0630926	823, 47029029912 -952, 8871629794 -823, 4702902991 952, 8871629794	1259, 4035351611 -49, 16699332 1259, 4035351611 130, 8330668	119417429015E9 120543392093E7 -30379345999E8 5527548, 9663513 -11821199509E9 359068949654E8
SDU2-A	153057, 99903954 -127548, 3811926 141001, 61863725 -133464, 1720449	199249, 7 -39, 8100000 195530, 04466358 -43, 8525528	588, 55894767894 -681, 8759410773 588, 558947679 681, 87596107733	900, 75176030261 -49, 2009085 900, 75176030261 130, 7990915	885346061203E8 855978, 18904113 146423759439E8 6434035, 1081480 -87478627931E8 -82083408358E7
SNOR-A	143506, 00676599 -133307, 3436778 138639, 83447113 -136229, 1107887	195869, 4 -42, 8900000 194369, 17021086 -44, 4975033	488, 80531294307 -711, 9893551344 -488, 8053129431 711, 98935513444	863, 63156252313 -55, 52909550 863, 63156252313 124, 4709450	825299541032E8 149171, 89515723 185067056850E7 2446419, 0805786 -82380782080E8 -16060286405E8
SRIC-A	314535, 19245101 -286405, 7672218 298234, 11346367 -301898, 3991532	425394, 7 -42, 3200000 424365, 67939067 -45, 3498319	570, 88740874361 -552, 5965998949 -570, 8874087436 552, 59659989487	794, 52843604075 -44, 0672822 794, 52843604075 135, 9327178	168915517067E9 372452, 50704967 515281579862E7 8926234, 6604779 -16854306456E9 377341886186E7
SVOG-A	428134, 45106971 -57110, 12152084 411938, 68828588 -105921, 802317	431926, 7 -7, 5980000 425338, 58408656 -14, 4200831	1760, 7653253694 -460, 0553985252 -1760, 765325369 460, 05539852519	1819, 8751332812 -84, 6429698 1819, 8751332812 165, 3570302	390059057878E9 303043013317E7 482040219039E8 4698431, 5603682 -38702862774E9 -15055903435E7
SHAT-A	409622, 80795653 -126329, 5330724	428660, 7 -17, 1400000	2738, 3443873862 -1117, 513523637	2957, 5947084484 -22, 2002848	631431639378E9 349894658378E7 559126298158E8 87473664, 5944180

Bus K	Bus M	Phasor node Rectangular	Phasor node voltage Polar	Phasor branch Rectangular	Phasor branch current Polar	Power flow P and Q	Power Loss P and Q
MART-A	TERRA	104505 .61780328	424269 .2886352	1153 .5233344526	5541 .7441688685	.11746930126E10	.11746930126E10
		-411197 .0392969	-75 .7401998	-5420 .360905886	-77 .9859423	.460663926498E8	.46066392 .6497815
		0.0	0.0	-1153 .523334453	5541 .7441688685	0.0	0.0
		0.0	0.0	5420 .3609058863	102 .0140577	0.0	0.0
MIDW-A	TERRA	126350 .66309265	420874 .93228093	692 .33240050768	2306 .1640124983	.485303311294E9	.485303311294E9
		-401461 .3537547	-72 .5298119	-2199 .788239752	-72 .5298119	-6082700565E-8	0.0000000
		0.0	0.0	-692 .3324005077	2306 .1640124983	0.0	0.0
		0.0	0.0	2199 .7882397516	107 .4701881	0.0	0.0
DUVA-A	TERRA	316577 .1634286	423910 .55695463	131 .45238618658	146 .31667283553	.298649534058E8	.298649534058E8
		-281920 .304404	-41 .4859059	-64 .25604185998	-26 .0501289	-.83585505373E7	-.8358550 .5373144
		0.0	0.0	-131 .4523861866	146 .31667283553	0.0	0.0
		0.0	0.0	64 .256041859981	153 .9498711	0.0	0.0
DUV2-A	TERRA	141001 .61863725	195530 .04466358	2439 .9117184376	3148 .9503880515	.306847171069E9	.306847171069E9
		-135464 .1720449	-43 .8525528	-1990 .658020013	-39 .2100758	-.24917308913E8	.24917308 .9129307
		0.0	0.0	-2439 .911718438	3148 .9503880515	0.0	0.0
		0.0	0.0	1990 .6580200126	140 .7899242	0.0	0.0
NORM-A	TERRA	138639 .83447113	194369 .17021086	597 .63319545014	1139 .5032600221	.107513123871E9	.107513123871E9
		-136229 .1107887	-44 .4975033	-970 .2073197502	-58 .3675521	.265471717094E8	.26547171 .7094405
		0.0	0.0	-597 .6331954501	1139 .5032600221	0.0	0.0
		0.0	0.0	970 .20731975025	121 .6324480	0.0	0.0
SANF-A	TERRA	79602 .743236744	196196 .13994243	1641 .7686934134	2652 .21481086	.252107283562E9	.252107283562E9
		-179321 .8575564	-66 .0630926	-2082 .987988509	-51 .7555414	-.64296726683E8	.64296726 .8832018
		0.0	0.0	-1641 .768693413	2652 .21481086	0.0	0.0
		0.0	0.0	2082 .9879885091	128 .2444586	0.0	0.0
MART-A	TERRA	385081 .86197388	425159 .90990629	-2738 .344387386	2957 .5947084484	-.62793269279E9	-.62793269279E9
		-180202 .4100012	-25 .0776531	1117 .5135236372	157 .7997152	.315610347786E8	.315610347786E8

LMCI -A	381271.48821561	421578.84105256	716.21075870842	882.83372904117	-182963068538E9	-182963068538E9
	-179890.9989329	-25.2588124	-516.1758830506	-35.7804394	.339816391406E8	33981639.1405877
TERRA	0.0	0.0	-716.2107587084	882.83372904117	0.0	0.0
	0.0	0.0	516.17588305059	144.2195606	0.0	0.0
DUVA -A	316577.16536286	423910.55695463	906.02324183102	1155.8254718863	.244576418E9	40077.975643841
	-281920.306404	-41.6859059	-717.6729106795	-38.3832072	-.14113765848E8	9044263.1702920
T1	306805.51375775	425030.33525647	-906.023241831	1155.8254718863	-.24453634002E9	
	-294144.7987238	-43.7930812	717.67291067948	141.6167928	.231580090182E8	
POIN -A	195640.41246027	423851.31153571	141.6769661575	251.94639267316	.530261975265E8	3802.271388385
	-375998.3554524	-62.5110244	-208.3377595191	-55.7829270	-.6255510538E7	859478.3759350
T4	189981.65303195	424674.78297869	-141.6769661575	251.94639267316	-.53022395255E8	
	-379810.0088324	-63.4256994	208.33775951907	124.2170730	.711498891261E7	

APPENDIX F HARMONIC ANALYSIS OF OUTPUTS OF HFCLC CYCLOCONVERTER

Table F.1 The harmonic analysis of HFCLC cycloconverter.

HARMONIC ANALYSIS OF OUTPUTS OF HFCLC CYCLOCONVERTER in SIMPLE AC POWER SYSTEM							
	400 mH T/L system					100 mH T/L system	
	V_0	V_1	V_2	V_3	Line current	V_0	Line current
0	0.0041	0.0032	0.0024	0.0019	0.0298	0.0030	0.0037
1	1	1	1	1	1	1	1
2	0.0016	0.0012	0.0012	0.0013	0.0346	0.0074	0.0040
3	0.0125	0.0073	0.0024	0.0005	0.0075	0.0033	0.0010
4	0.0066	0.0038	0.0010	0.0002	0.0117	0.0114	0.0023
5	0.0163	0.0094	0.0029	0.0001	0.0145	0.0105	0.0024
6	0.0062	0.0036	0.0012	0.0001	0.0039	0.0100	0.0016
7	0.0139	0.0080	0.0024	0.0	0.0083	0.0171	0.0027
8	0.0029	0.0017	0.0005	0.0	0.0030	0.0053	0.0006
9	0.0014	0.0008	0.0002	0.0	0.0022	0.0200	0.0024
10	0.0230	0.0133	0.0041	0.0	0.0015	0.0303	0.0028
11	0.0124	0.0072	0.0022	0.0	0.0028	0.0323	0.0027
12	0.0173	0.0100	0.0031	0.0	0.0023	0.0233	0.0018
13	0.0309	0.0178	0.0055	0.0	0.0036	0.0302	0.0027
14	0.0158	0.0092	0.0028	0.0	0.0074	0.0247	0.0017
15	0.0062	0.0036	0.0011	0.0	0.0042	0.0059	0.0002
16	0.0017	0.0010	0.0003	0.0	0.0040	0.0528	0.0032
17	0.0038	0.0021	0.0	0.0	0.0043	0.0064	0.0005
18	0.0576	0.0333	0.0104	0.0	0.0047	0.0667	0.0038
19	0.0423	0.0245	0.0076	0.0	0.0063	0.0261	0.0014
20	0.0703	0.0407	0.0127	0.0	0.0053	0.0287	0.0015
21	0.0288	0.0166	0.0052	0.0	0.0081	0.0348	0.0015
THD	11.77%	6.81%	2.13%	0.14%	4.47%	12.34%	1.03%

Harmonic analysis of outputs of the HFLC cycloconverter in two simple ac power systems was performed. One had transmission line (T/L) inductance of 150 mH. The other had 400 mH T/L inductance. The operating conditions were 5 KHz tank frequency, 0.7 μ F tank capacitance, 1.3 MV tank voltage, 2828 A peak line current and 408 KV peak line voltage.

Outputs from 150 mH T/L system are called unfiltered outputs and outputs from 400 mH T/L system are called filtered outputs. The line voltages in the 400 mH case were analyzed at every one-fourth of T/L to show the attenuation of the harmonics along the length of the T/L.

Table F.1 shows the normalized magnitude of the harmonic components of the line voltage and the line current. In Table F.1, V_0 is the line voltage at the terminal of the HFLC cycloconverter, V_1 is the line voltage at the one-fourth of the T/L from the terminal of the HFLC cycloconverter, V_2 is the line voltage at the middle of the T/L from the terminal of the HFLC cycloconverter, V_3 is the line voltage at the three-fourth of the T/L from the terminal of the HFLC cycloconverter.

APPENDIX G

DESIGN OF CAPACITANCE OF THE TANK CIRCUIT

The selection of the capacitor size of the tank circuit is critical to the operation of the HFLCs in the ac power transmission system because it determines the tank voltage ripple. The required capacitance for the proper high frequency operation depends on the topology of the HFLCs in the ac power transmission system. Simple circuit analysis can be used to derive the proper tank capacitance required to meet proper ripple specification for each HFLC circuit.

G.1 HFLC Cycloconverter Case

Fig. G.1 shows the tank circuit in the HFLC cycloconverter connected to the simplified two-bus three-phase ac power transmission system for an arbitrary switching period.

From simple circuit analysis, the tank voltage, $V_t(t)$ is expressed as

$$V_t(t) = \frac{i_3(0) + i_t(0)}{C \sqrt{\frac{2L_d + 3L_t}{2C L_t L_d}}} \sin\left(\sqrt{\frac{2L_d + 3L_t}{2C L_t L_d}} t\right) \quad (G.1)$$

For proper high frequency operation, it is assumed that

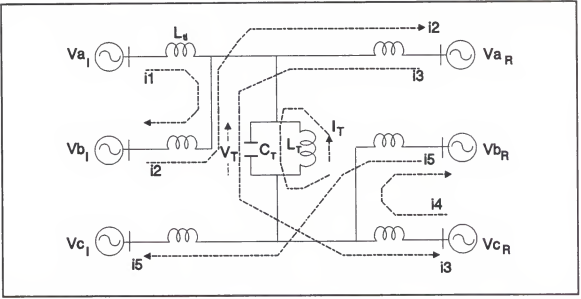


Fig. G.1 The tank circuit of the HFLC cycloconverter connected to the simplified two-bus three-phase ac power transmission system.

$$2L_d > 3L_t \quad (G.2)$$

Then, equation (G.1) simplifies to

$$V_t(t) \approx \frac{i_3(0) + i_t(0)}{\sqrt{\frac{C_t}{L_t}}} \sin\left(\frac{t}{\sqrt{C_t L_t}}\right) \quad (G.3)$$

Then, using equations (2.1), (2.13) and (2.19), equation (G.3) becomes

$$V_t(t) = \left(\frac{I_{sp}}{\omega_h C_t} + V_p\right) \sin(\omega_h t) \quad (G.4)$$

From simple circuit analysis, the relation between the loop current, I_3 , the line current, I_{cr} , the current flowing into the tank circuit, I_{sp} , can be expressed as

$$I_{sp} = I_3 = 2I_{cr} \quad (G.5)$$

Then, by using the equations (2.22) and (2.26), the proper size of the capacitance for the normalized ripple ΔV_m in the HFLC cycloconverter is expressed as

$$C_t = \frac{2I_{cr}}{\omega_h V_t \Delta V_m} \quad (G.6)$$

G.2 HFLC Series Compensator Case

Fig. G.2 shows the connection of the tank circuit of the HFLC series compensator to the simplified ac power transmission system for an arbitrary switching period. To simplify the analysis of the circuit, the power angle, δ , between the system I and the system R is assumed to be zero.

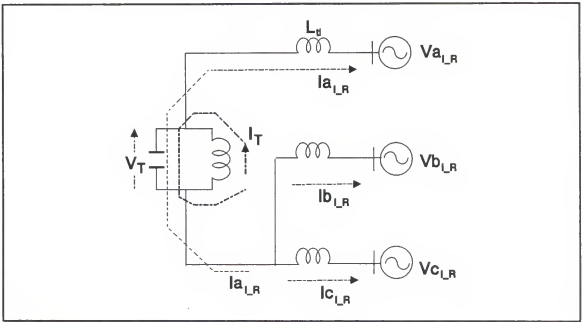


Fig. G.2 The tank circuit of the HFLC series compensator connected the simplified two-bus three-phase ac power transmission system.

To ensure proper HFLC operation, it is again assumed that

$$3L_d > 2L_t \quad (G.7)$$

From Fig. G.2, the current flowing into the tank circuit, I_{tp} , equals the line current, I_a . Then, from the circuit analysis which is similar to that of HFLC cycloconverter, the tank voltage, $V_t(t)$ is expressed as

$$V_t(t) = \frac{i_{a_v}(0) + i_t(0)}{\sqrt{\frac{C_t}{L_t}}} \sin\left(\frac{t}{\sqrt{C_t L_t}}\right) \quad (G.8)$$

Using equations (2.1), (2.13) and (2.19), equation (G.8) simplifies to

$$V_t(t) = \left(\frac{I_{a_v}}{\omega_h C_t} + V_{\varphi} \right) \sin(\omega_h t) \quad (G.9)$$

Then, using the equations (2.22) and (2.26), the proper size of the capacitor in the HFLC series compensator to meet desired ripple specification is

$$C_t = \frac{I_{a_v}}{\omega_h V_t \Delta V_m} \quad (G.10)$$

Equations (G.4), (G.5) and (G.9) show that the line current influences the ripple in the tank voltage in the HFLC cycloconverter more than in the HFLC series compensator. Equations (G.6) and (G.10) explain that the capacitance size depends on the topology of HFLC circuit and that the HFLC cycloconverter, because of the higher tank voltage, requires smaller capacitor for the specified ripple size than HFLC series compensator.

REFERENCE LIST

- [1] C.P. Arnold, R.M. Duke and J. Arrillaga, "Transient Stability Improvement Using Thyristor Controlled Quadratic Voltage Injection," IEEE Transactions on Power Apparatus and Systems, Vol. PAS_100, No.3 March 1981, pp. 1382--1388.
- [2] B.J. Baliga, "Switching Lots of Watts at High Speeds," IEEE Spectrum, Vol. 18, No. 12, December 1981, pp. 42--48.
- [3] B.V. Borges, "Prediction Current Injected Control Applied to DC-AC Parallel Resonant Converters," IEEE Power Electronics Specialists Conference, 1989 Record, pp. 71--76.
- [4] G.D. Breuer, P.F. Albrecht, C. Bowler, E.V. Larsen, R.J. O'Keefe, J.J. Paserba, R.J. Piwko and A.T. Tsuchiya, "Flexible AC Transmission System (FACTS): Scoping Study," Electric Power Research Institute Project 3022-2, Final Report, EPRI EL-6943s Vol. 2, General Electric Company, September 1991.
- [5] D.P. Carroll, K.D.T. Ngo, G.B. Chung, A. Maheshwari and S.B. Swindler, "High Frequency Link Converters As Elements in Flexible AC Transmission System," Annual Report(Project RP4000-19) submitted to EPRI, University of Florida, October 1991.
- [6] D.Y. Chen, "Power Semiconductors: Fast, Tough and Compact," IEEE Spectrum Vol. 24, No. 9, September 1987, pp. 30--35.
- [7] D.M. Divan, "The Resonant DC Link Converter ---A new Concept in Static Power Conversion," in Conf. Rec. 1986 Annu. Meet. IEEE Ind. Appl. Soc., p.p. 648--655.

- [8] D.M. Divan, "Inverter Topologies and Control Techniques for Sinusoidal Output Power Supplies," IEEE Power Electronics Specialists Conference, 1991 Record, pp. 81--87.
- [9] P.M. Espelage and B.K. Bose, "High-Frequency Link Power Conversion," IEEE Transactions on Industry Applications, Vol. 13, No. 5, September/October 1977, pp. 387--394
- [10] A.M. Gole and R.W. Menzies, "Analysis of Certain Aspects of Forced Commutated HVDC Inverters," IEEE Transaction on Power Apparatus and Systems, Vol. PAS-100, No. 5, May 1981, p.p. 2258--2262.
- [11] A.M. Gole and V.K. Sood, "A Static Compensator Model for Use with Electromagnetic Transients Simulation Programs," IEEE Transactions on Power Delivery, Vol. 5, No.3, July 1990, pp 1398--1405.
- [12] L. Gyugyi, "Static Power Frequency Changers," John Wiley and Sons, New York, 1976
- [13] L. Gyugyi, "Reactive Power Generation and Control by Thyristor Circuits," IEEE Transactions on Industry Applications, Vol. IA-15, No. 4, July/August 1979, pp.420--429.
- [14] L. Gyugyi, "Solid-State Control of AC Power Transmission," EPRI workshop on the Future in High Voltage Transmission, Cincinnati, Ohio, November 1990.
- [15] L. Gyugyi and F. Cibilka, "The High-Frequency Base Converter --- A New Approach to Static High-Power Conversion," IEEE Transactions on Industry Applications, Vol. IA-15, No. 4, July/August 1979, pp.420--429.
- [16] J. He and N. Mohan, "Switch-Mode VAR Compensator with Minimized Switching Losses and Energy Storage Elements," IEEE Transaction on Power Systems, Vol. 5, No. 1, February 1990, pp. 90--95.

- [17] C. P. Henze, H.C. Martin and D.W. Parsley, "Zero-Voltage Switching in High Frequency Power Converters Using Pulse Width Modulation," IEEE Applied Power Electronics Conference, 1988 Record, pp. 33-40.
- [18] N.G. Hingorani, "Power Electronics in Electric Utilities: Role of Power Electronics in Future Power System," Proceedings of the IEEE, Vol. 76, No. 4, April, 1988, pp. 481--482
- [19] M.H. Kheraluwala and D.M. Divan, "Delta Modulation Strategies for Resonant Link Inverters," IEEE Transactions on Power Electronics, Vol.5, No.2, April, 1990, pp. 220-228.
- [20] E.W. Kimbark, "Direct Current Transmission, Volume I", John Wiley and Sons, New York, 1971.
- [21] B. C. Kuo, "Modern Control Systems, Prentice-Hall, Englewood Cliffs, New Jersey, 1967.
- [22] K. Liu and F. C. Lee, "Zero-Voltage Switching Technique in DC/DC Converters," IEEE Power Electronics Specialists Conference, 1986 Record, pp. 55-70.
- [23] K. Liu, R. Oruganti and F.C. Lee, "Resonant Switches - Topologies and Characteristics," IEEE Power Electronics Specialists Conference, 1985 Record, pp. 106-116.
- [24] R.D. Lorenz, D.M. Divan, "Dynamic Analysis & Experimental Evaluation of Delta Modulators for Field Oriented AC Machine Current Regulators," IEEE Power Electronics Specialists Conference, 1987 Record, pp. 196--201.
- [25] T.J.E. Miller, "Reactive Power Control in Electric Systems," John Wiley & Sons, New york, 1982.

- [26] L. T. Moran, P. D. Ziogas and G. Joos, "Analysis and Design of a Novel 3- ϕ Solid-State Power Factor Compensator and Harmonic Suppressor System," IEEE Transactions on Industry Applications, Vol. 25, No.4, July/August 1989, pp. 609--619.
- [27] K. D. T. Ngo, "Analysis of a Series-Resonant Converter Pulsewidth-Modulated or Current-Controlled for Low Switching Loss," IEEE Transactions on Power Electronics, Vol. 3, No.1, January 1988, pp. 55--63.
- [28] J. Nishizawa, "SI Thyristor Hold Promise for Improved DC Power Transmission," Power Conversion Intelligent Motion, October 1988, pp 32--34.
- [29] D. O'Kelly and G. Musgrave, "Improvement of Power-System Transient Stability by Phase-Shift Insertion," PROC. IEE, Vol. 120, No.2, February 1973, pp. 247--252.
- [30] B. Ooi and S. Dai, "Series-Type Solid-State Static VAR Compensator," IEEE Power Electronics Specialists Conference, 1991 Record, pp. 3--9.
- [31] H. S. Patel and R. G. Hoft, "Generalized Techniques of Harmonic Elimination and Voltage Control on Thyristor Inverters: Part I-Harmonic Elimination," IEEE Transactions on Industry Applications, Vol. IA-9, No.3, May/June 1973, pp. 310--317.
- [32] F. C. Schwarz, "An Improved Method of Resonant Current Pulse Modulation for Power Converters," IEEE Power Electronics Specialists Conference, 1975 Record, pp. 194-204.
- [33] J.F. Silva, B.V. Borges and V. Anunciada, "Improving Control Strategies for HF Resonant Link Converters: The Current Mode Predictive Modulator," IEEE Power Electronics Specialists Conference, 1991 Record, pp. 268--275.
- [34] P.K. Sood and T.A. Lipo, "Power Conversion Distribution System Using a High-Frequency AC link," IEEE Transactions on Industry Applications, Vol. 24, No. 2, March/April 1988, pp. 288--300.

- [35] Y. Sumi and M. Yano, "New Static VAR Control using Forced-Commutated Inverters," IEEE Transactions on Power Apparatus and Systems, Vol. PAS_100, No.9, September 1981, pp. 4216--4224.
- [36] W. A. Tabisz and F. C. Lee, "Zero-Voltage-Switching Multi-Resonant Technique -- A Novel Approach to Improve Performance of High-Frequency Quasi-Resonant Converters," IEEE Power Electronics Specialists Conference, 1988 Record, pp. 9-17.
- [37] K. Tam and R. Lasseter, "A Study of Hybrid HVDC Converter," International Conference on DC Power Transmission, Montreal, Canada, June 1984, pp. 205--212.
- [38] V. A. K. Temple, "MCT's for High Frequency Applications," Proceedings of High-Frequency Power Conversion Conference, May 1988, pp. 62-80.
- [39] T. Wouvi and J. Houldsworth, "Active Switches for the High Frequency Power Conversion Compared," Proceedings of High Frequency Power Conversion Conference, May 1989, pp. 62--80.
- [40] K. Xing and G. Kusic, "Application of Thyristor-Controlled Phase Shifters to Minimize Real Power Losses and Augment Stability of Power Systems," IEEE Transactions on Energy Conversion, Vol. 3, No. 4, December 1988, pp. 792--798.
- [41] P. Ziogas, "The Delta Modulation Technique in Static PWM Inverters," IEEE Transactions on Industry Applications, Vol. IA_17, No. 2, March/April 1981, pp. 199--204.

BIOGRAPHICAL SKETCH

Gyo-Bum Chung was born on December 20, 1959, in Seoul, Korea. He received the B.S. and M.S. degrees in electrical engineering from Seoul National University, Seoul, Korea, in 1983 and 1985, respectively. In August, 1986, he came to Gainesville to do his Ph.D work in electrical engineering at the University of Florida. He expects to receive his degree in May, 1992.

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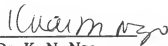
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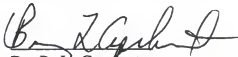
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